Computational Cameras and Illumination

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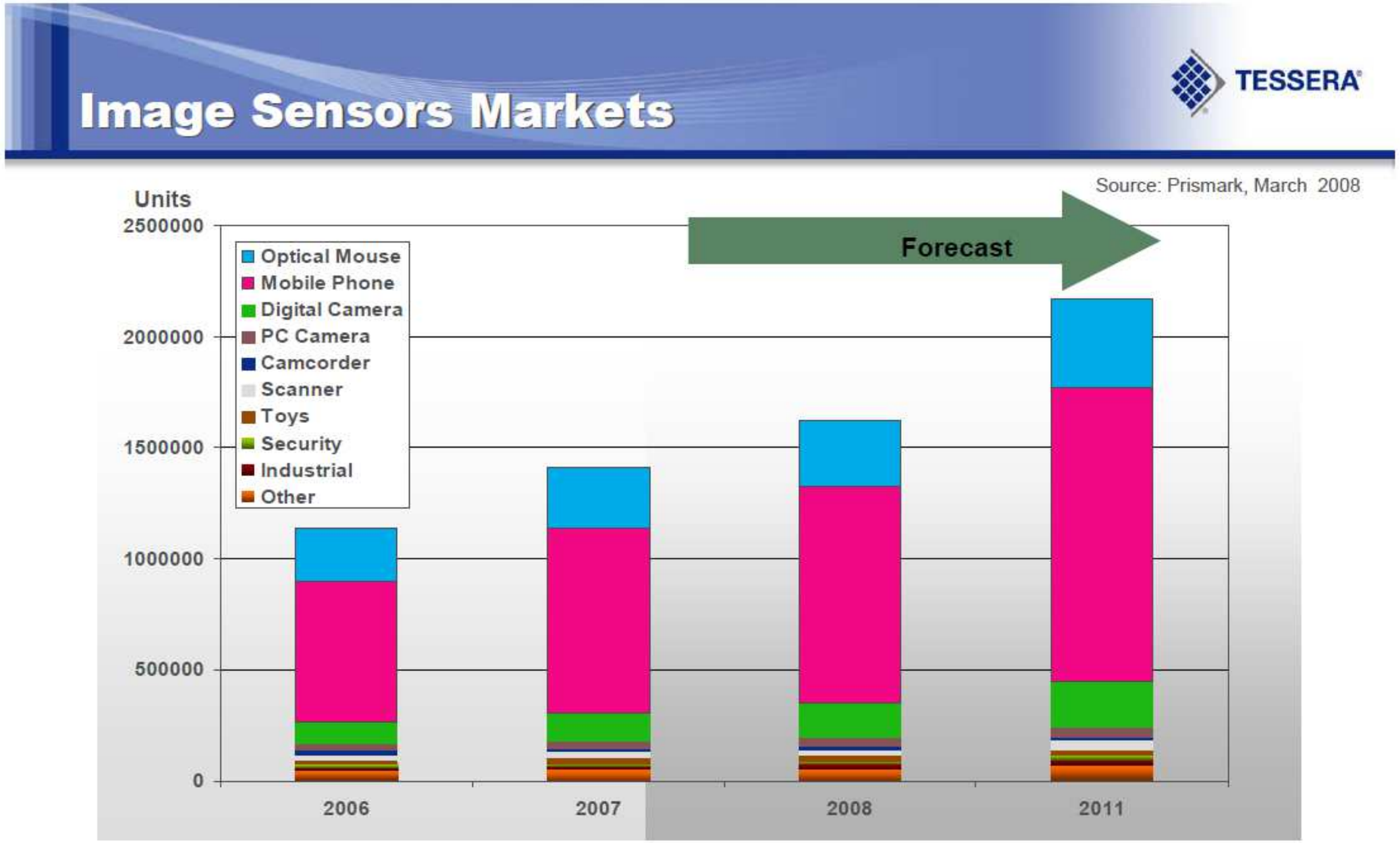
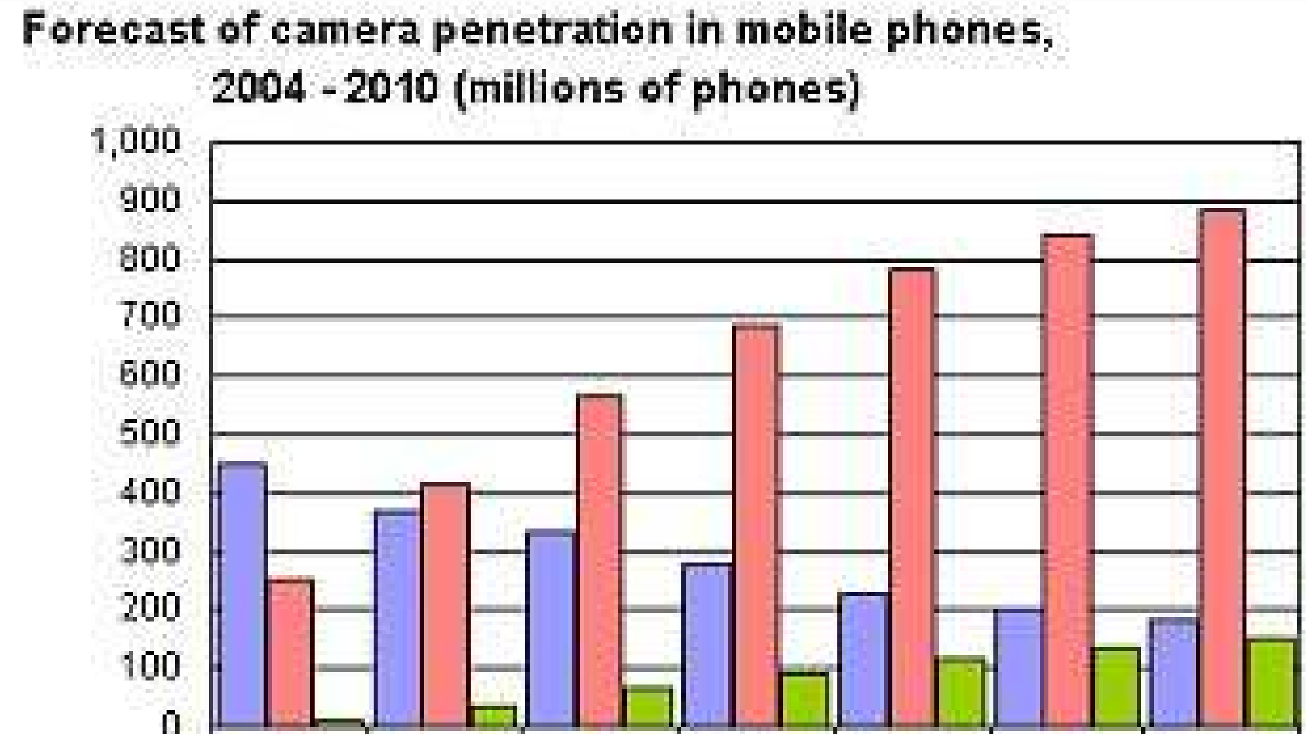
Where are the cameras?



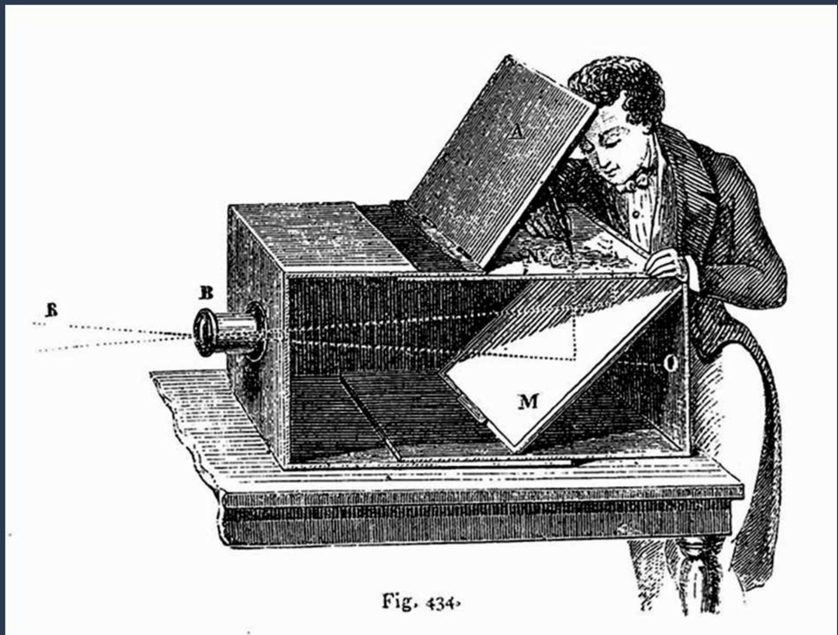
Cameras in Mobile Phones



	2004	2005	2006	2007	2008	2009	2010
No camera	451	371	334	275	226	200	180
Primary camera only	251	414	568	686	783	843	883
Primary and secondary camera	11	35	65	91	117	138	153

Source: iSuppli

Have Cameras Evolved?



Lens Based Camera Obscura, 1568

Digital Cameras

Have Projectors Evolved?

- Similar trends in form factor/Cost
  - Film/Slide projectors
  - Digital projectors
  - Pocket Projectors
  - Pico Projectors
  - Projectors in smartphones

Projector vs Cameras

- Current projectors offer capabilities far beyond current cameras
- Each projector pixel can be independently controlled
  - Allows coding and modulation of outgoing light

How about cameras where each pixel can be independently controlled?

Allow coding and modulation of incoming light?

Projectors vs Cameras

Exposure, Frame Rate, Resolution etc.

High level controls

Brightness, color temperature

Per Pixel Control?

Projectors vs Cameras

Exposure, Frame Rate, Resolution etc.

High level controls

Brightness, color temperature

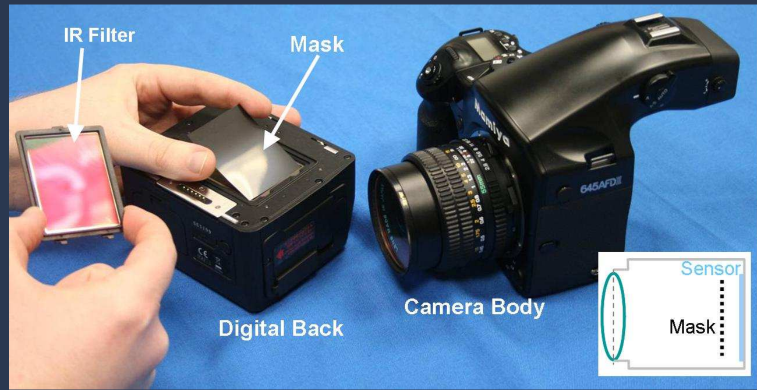
Per Pixel Control?

Computational Cameras

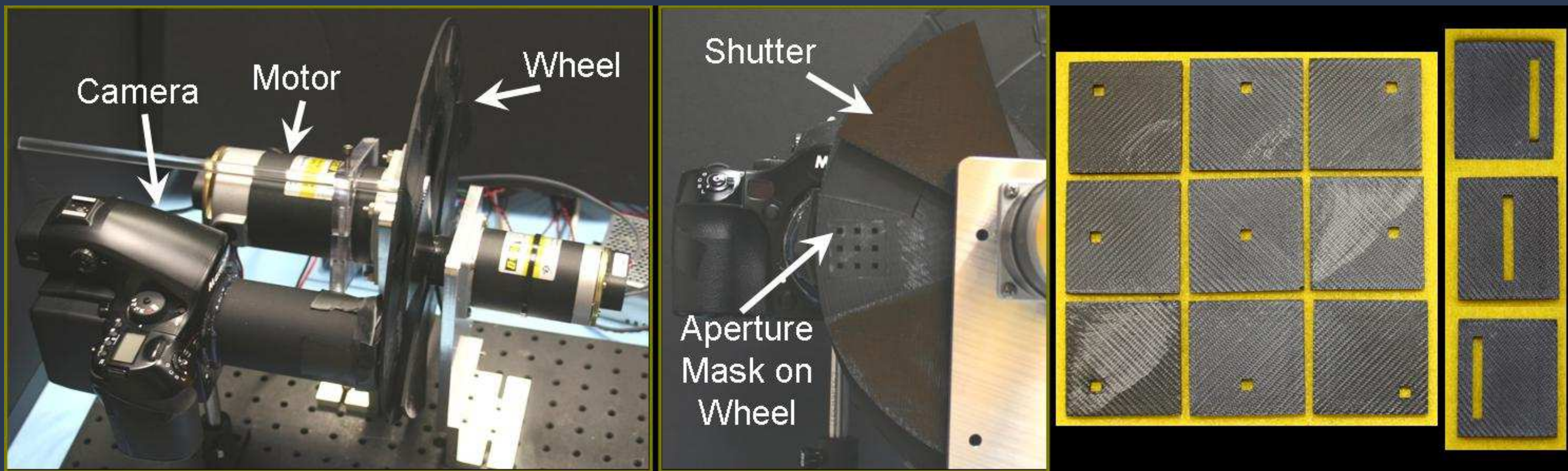
Computational Cameras

Flutter Shutter Camera

Coded Aperture Camera

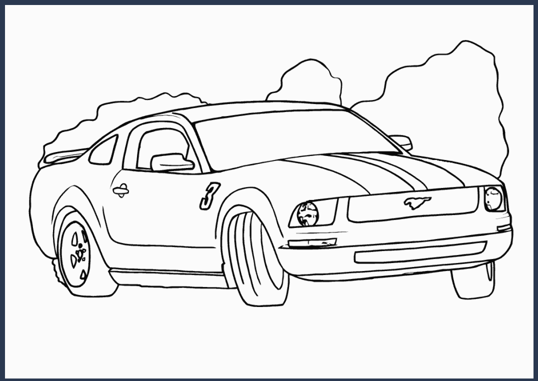


Mask based light field camera



Reinterpretable Camera

Not Mimicking Humans



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Computational Cameras

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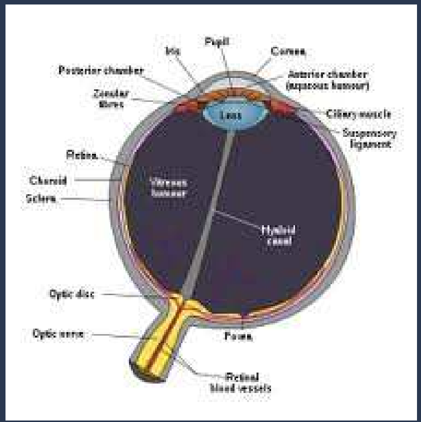


Not Mimicking Humans

- Scientific Imaging, Astronomy
  - Imaging capabilities beyond human vision
- Bring such ideas into
  - Computational photography
  - Computer vision

Computational Cameras and Illumination

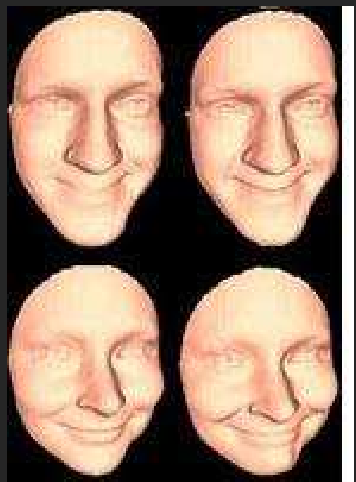
- Computational Illumination (Projector)
  - Structure Light
  - Design of new codes
  - Global Illumination

- Computational Cameras
  - Motion Blur, Focus Blur, Light Fields, Plenoptic Function

Advances in Structured Light Scanning

High depth resolution (~50 microns)

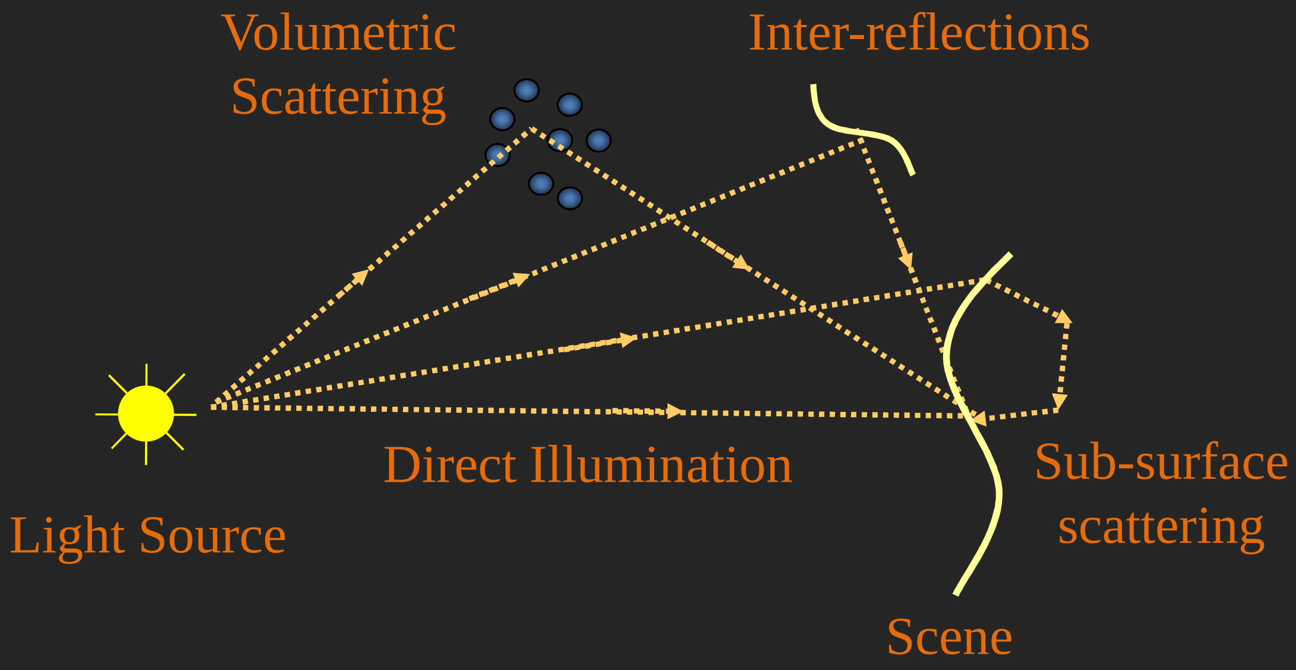
High speed (~4000 Hz.)

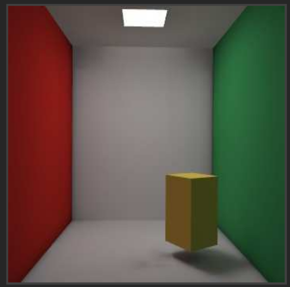


Zhang et al

Kinect

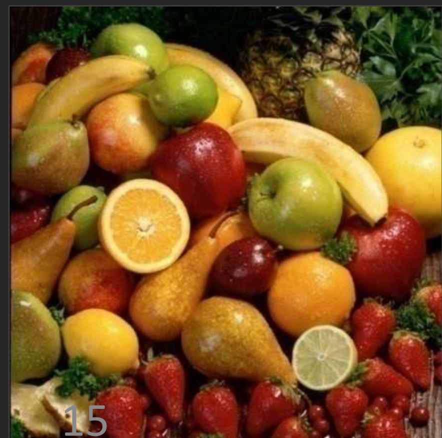
Light Transport





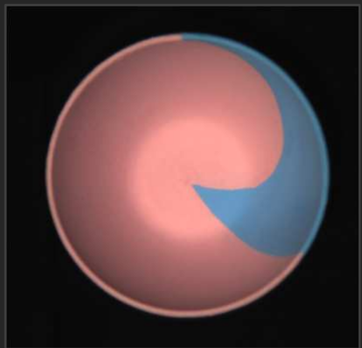
Slide adapted from Nayar et al

Global light transport in the world around us

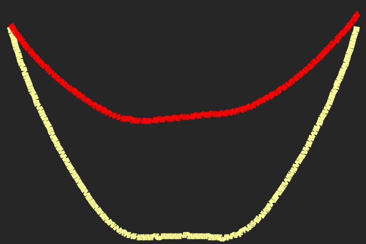


What happens if we ignore global light transport?

Photometric Stereo

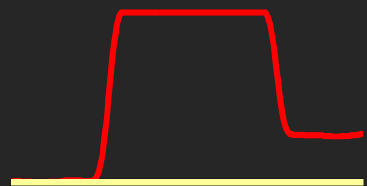


Nayar et al [1991, 2006]

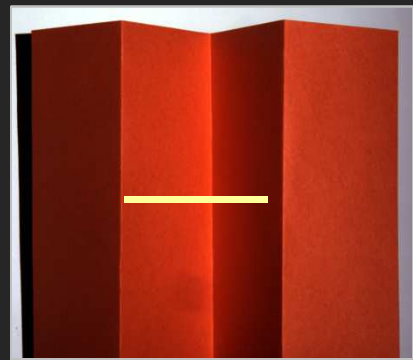


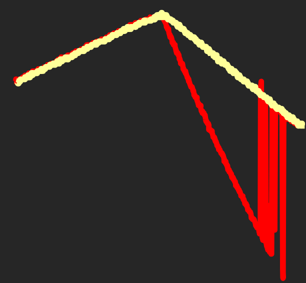
Shape from Illumination Defocus

Gupta et al [2009]



Structured Light Triangulation





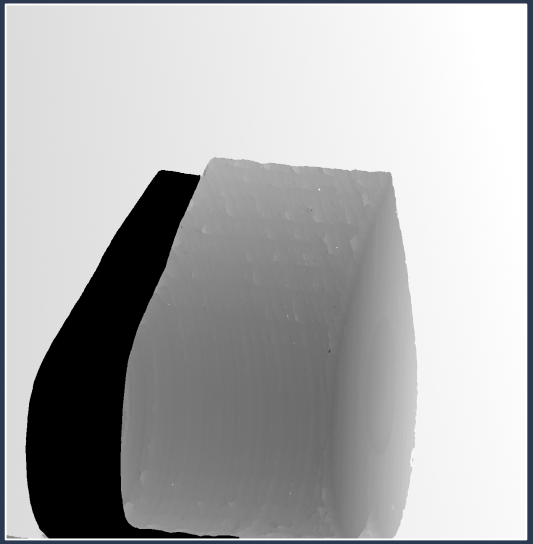
Estimated Shape   Ground Truth

Translucent Wax Object

Errors due to strong sub-surface scattering

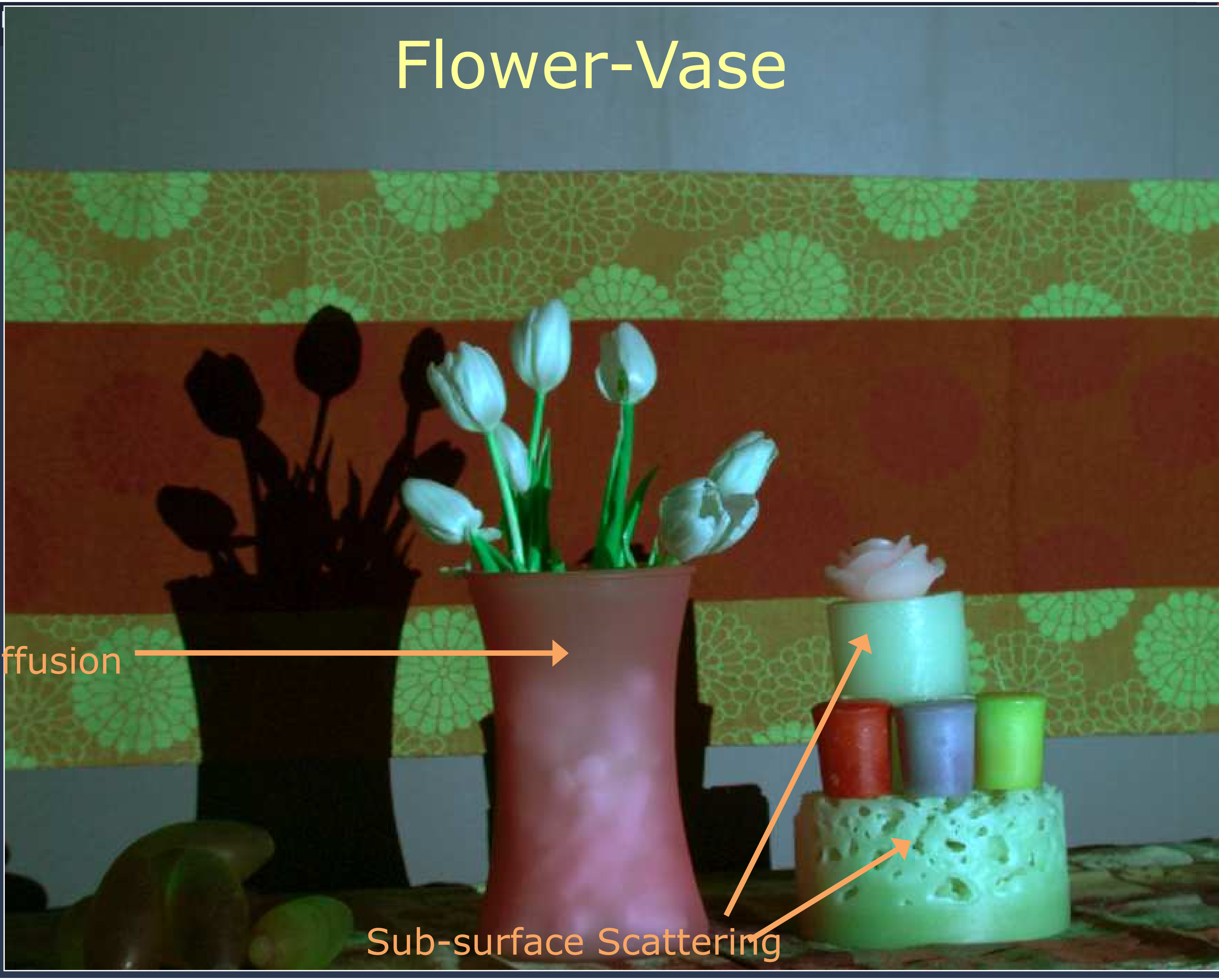
Scene

Modulated Phase-Shifting



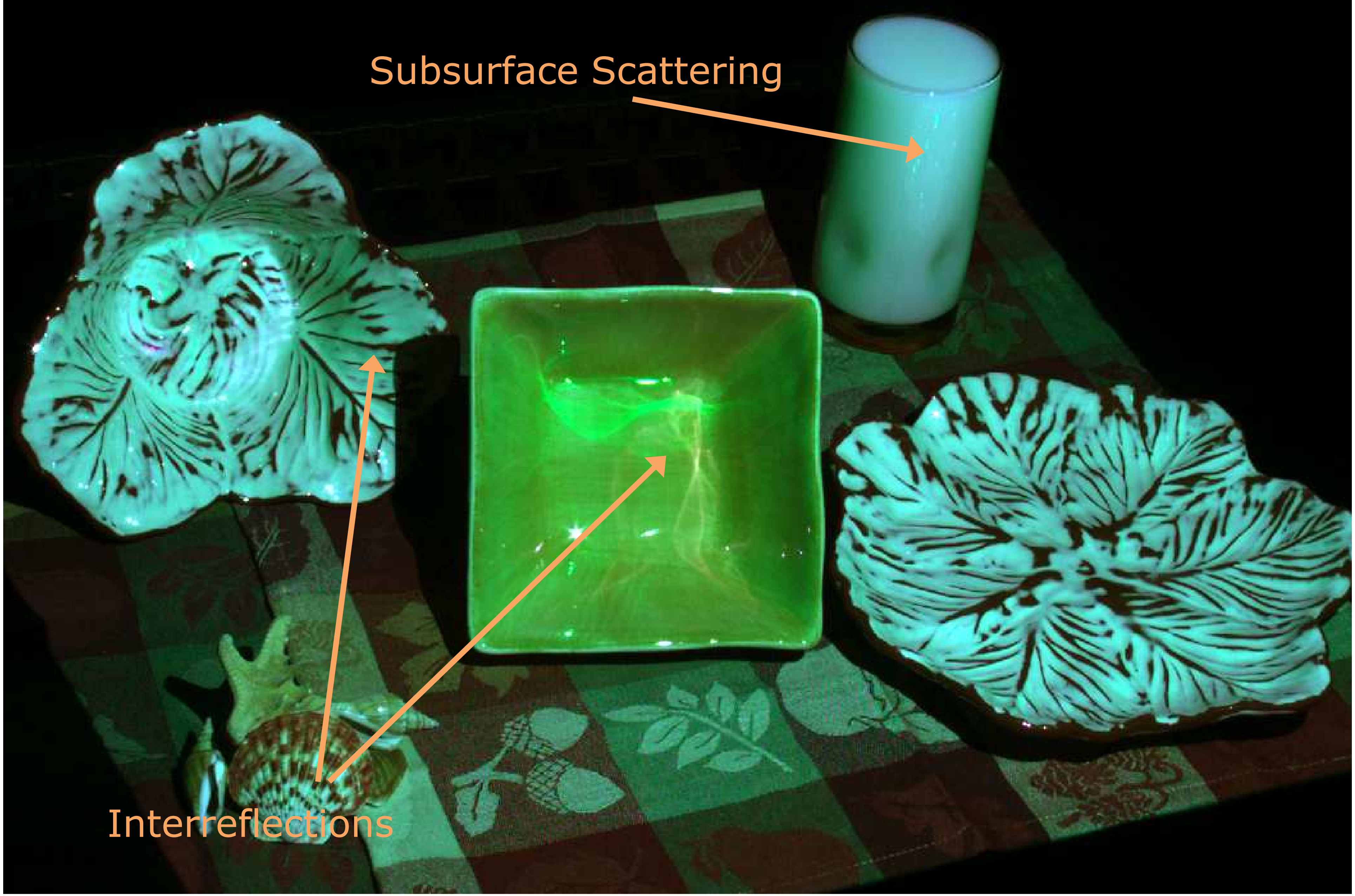
Ours

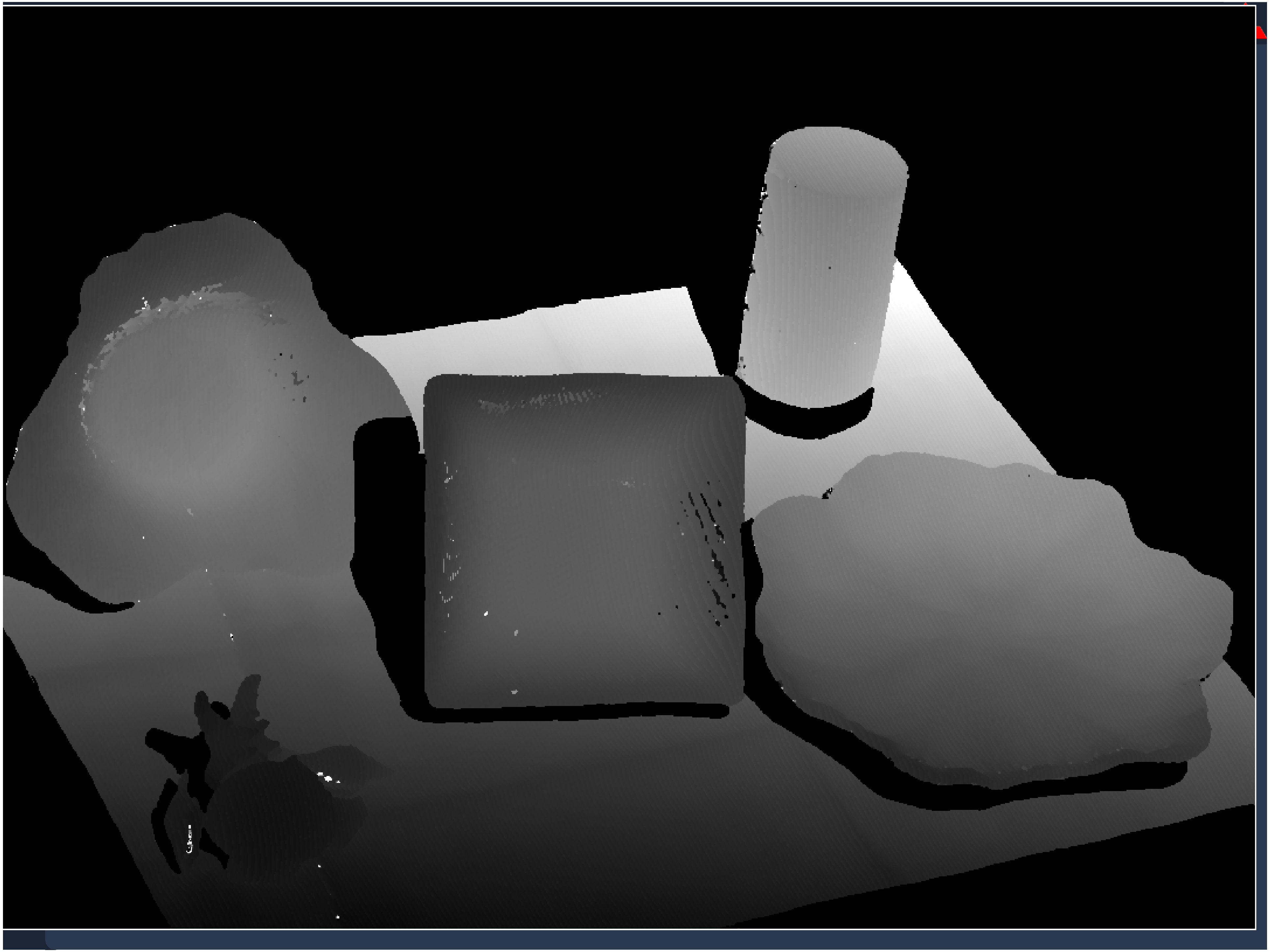
Flower-Vase

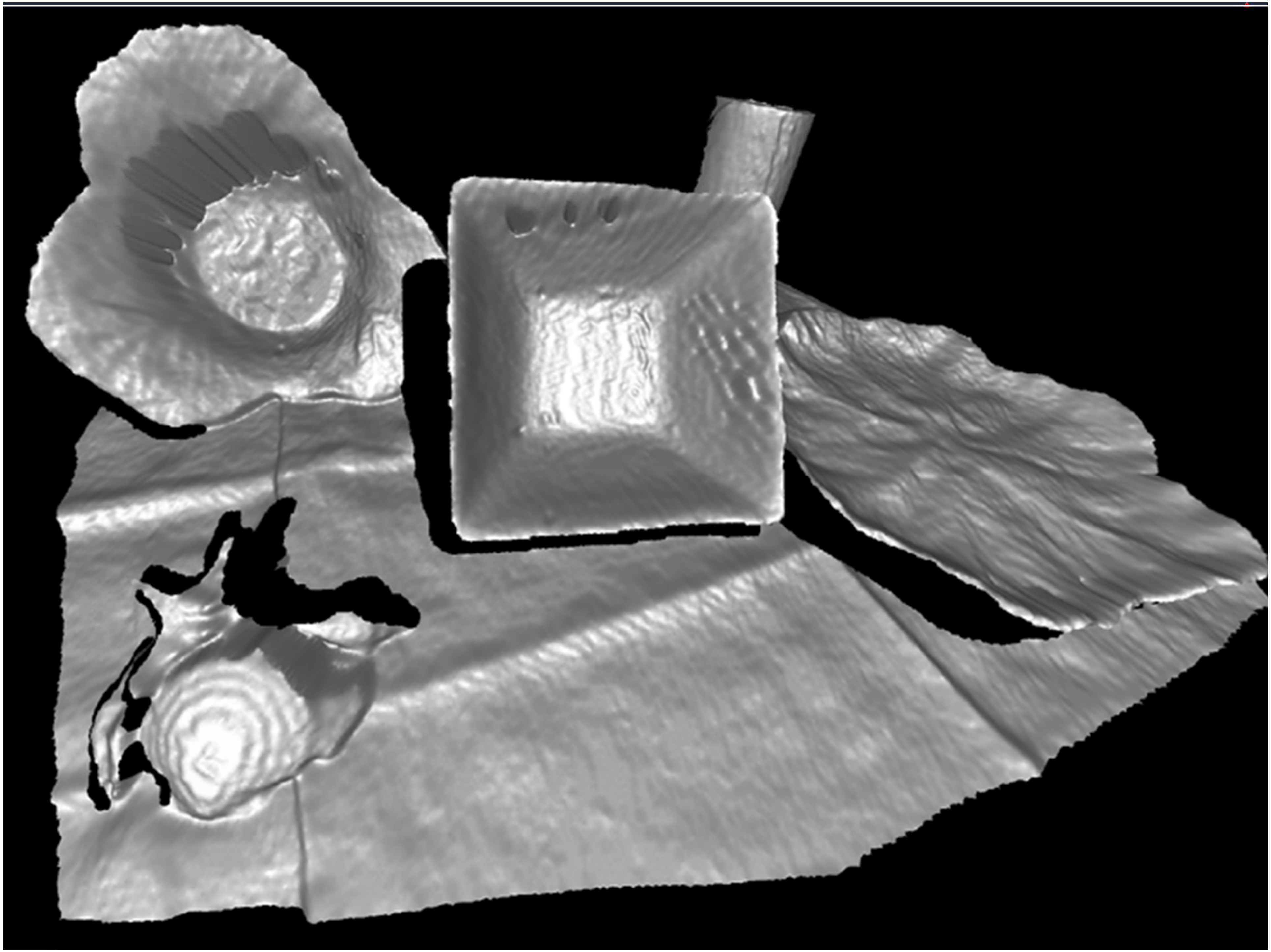


Reconstructed Depth Map

Bowls and Milk: Multiple Effects

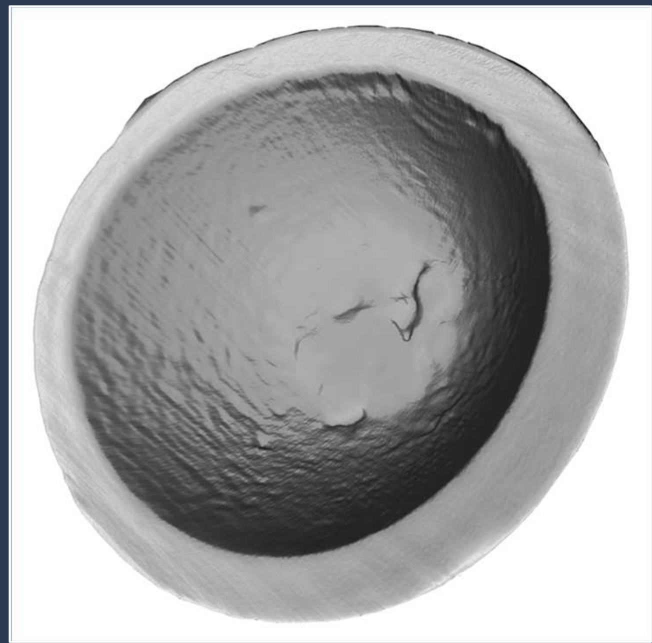






Multiple Global Illumination Effects

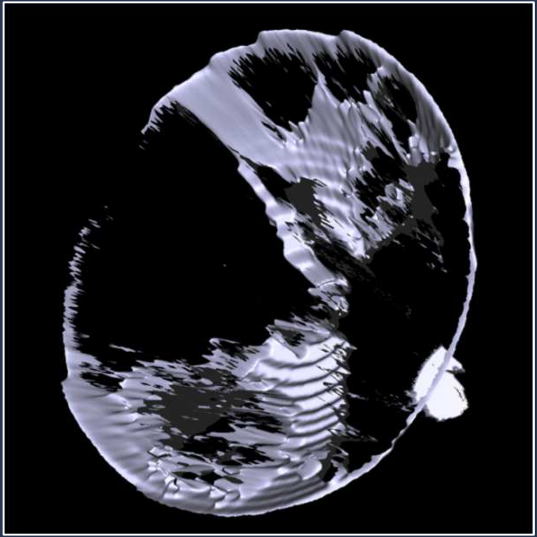
Wax Bowl



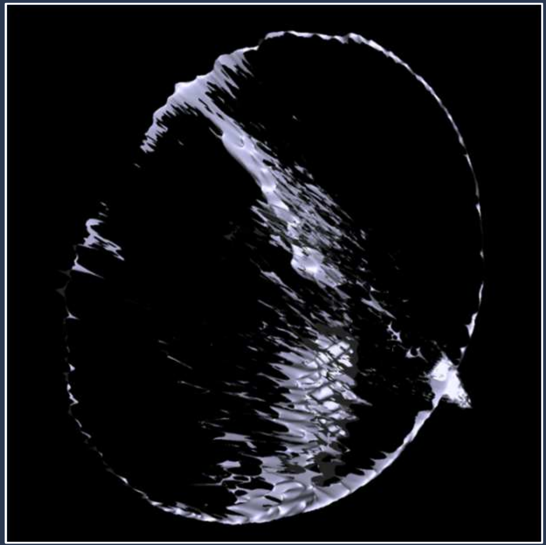
Inter-reflections +
Subsurface Scattering

Shiny Metallic Lamp

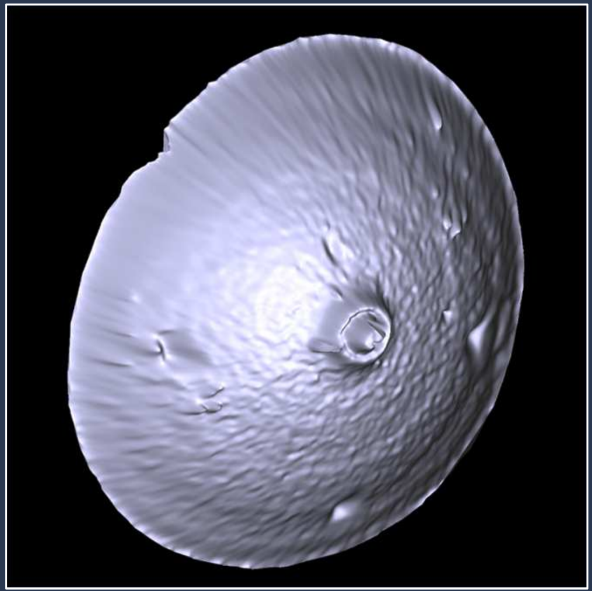
Strong and high-frequency inter-reflections



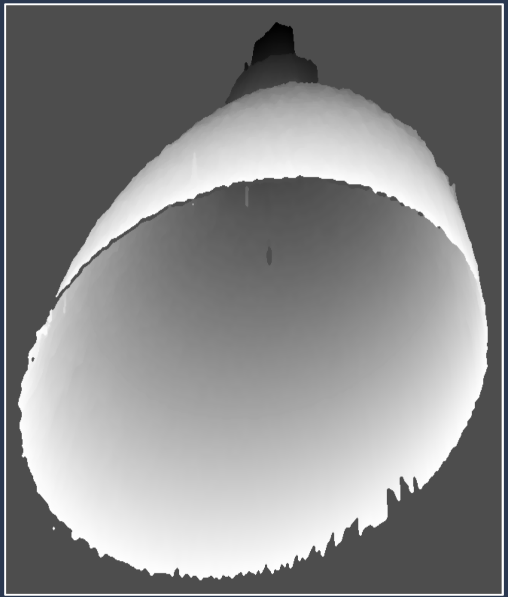
Regular Gray Codes



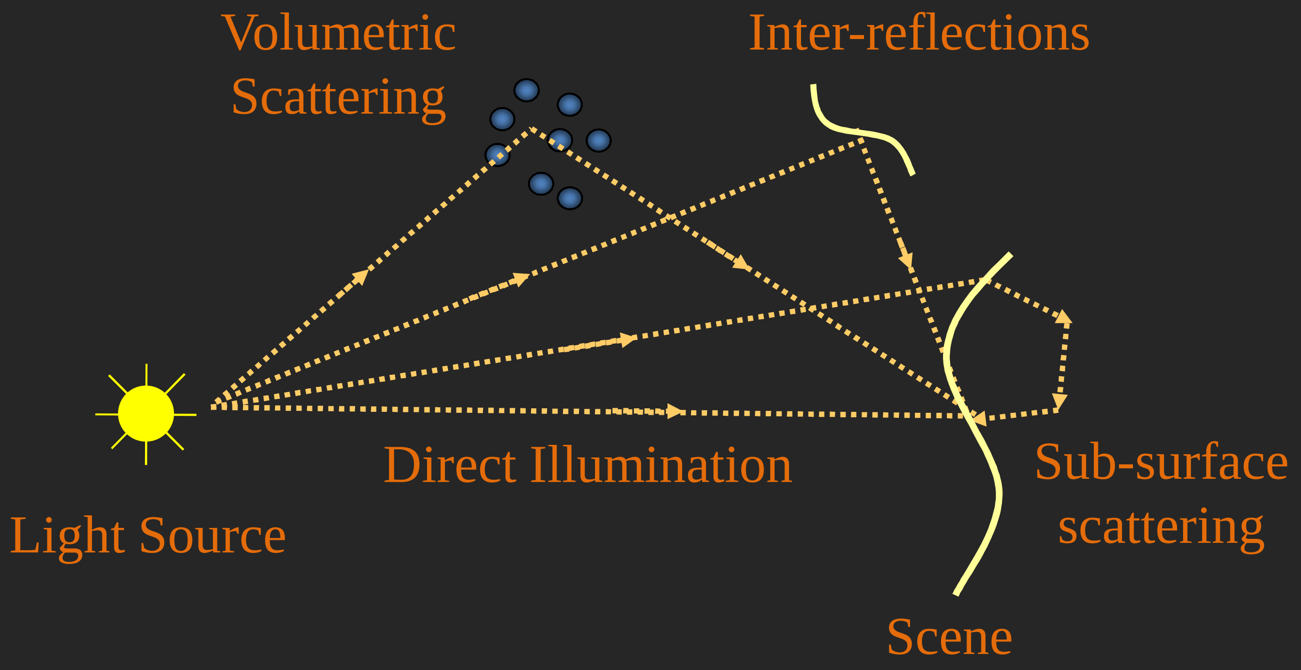
Modulated Phase Shifting

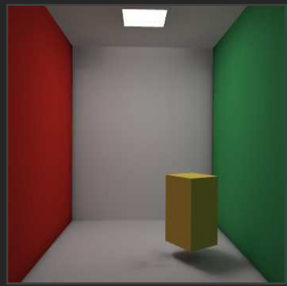


Ours



Light Transport



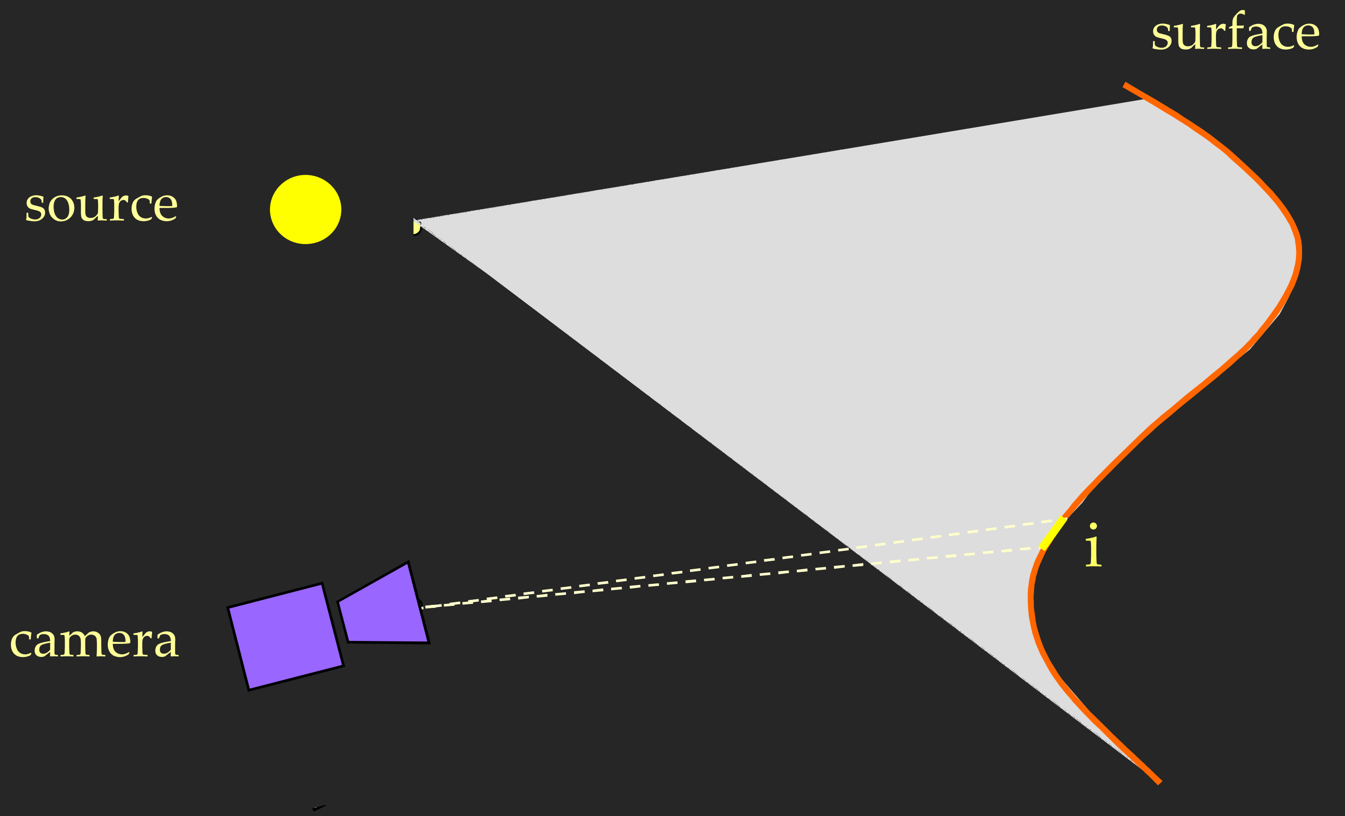


Slide adapted from Nayar et al

Direct Global Separation

- Separate direct and global components using high frequency illumination
  - Nayar et al. SIGGRAPH 2006
- Use only the direct component for shape estimation

Point Light Source Illuminating the Scene

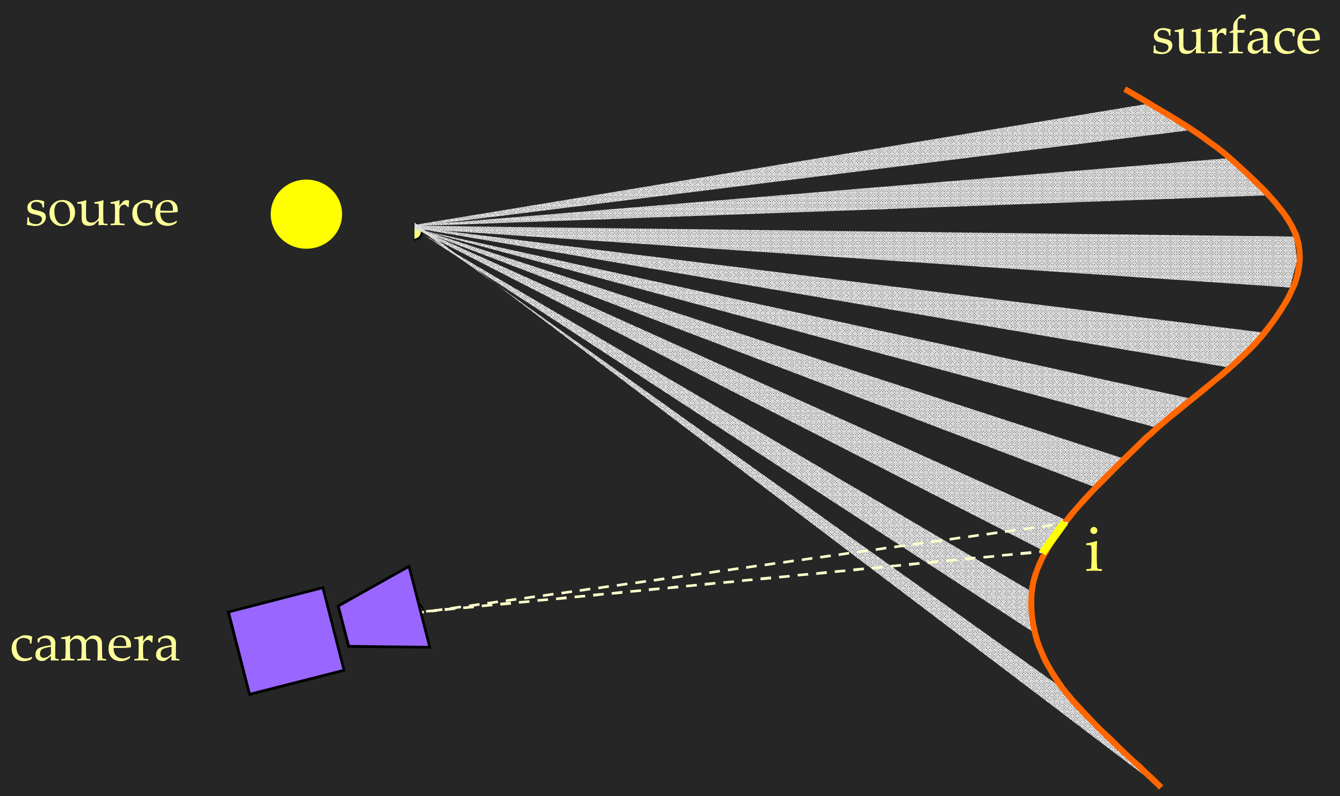


$$\boxed{L[i] = L_d[i] + L_g[i]}$$

Direct Component

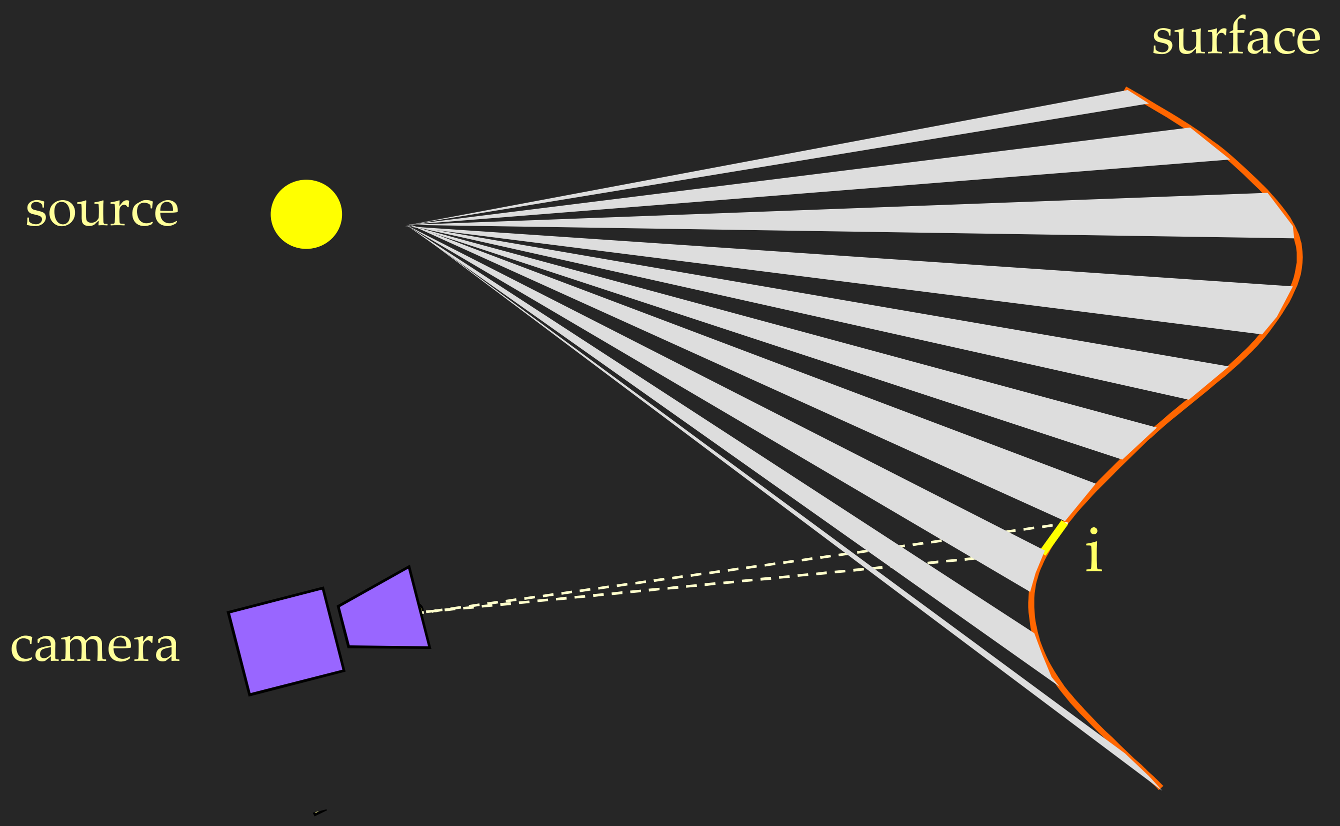
Global Component

Under High-Frequency Illumination



$$L_+[i] = L_d[i] + 0.5\, L_g[i]$$

Slide courtesy Nayar et al



$$L_+[i] = L_d[i] + 0.5\, L_g[i]$$

$$L_-[i] = 0.5\, L_g[i]$$

Slide courtesy Nayar et al

Direct Global Separation

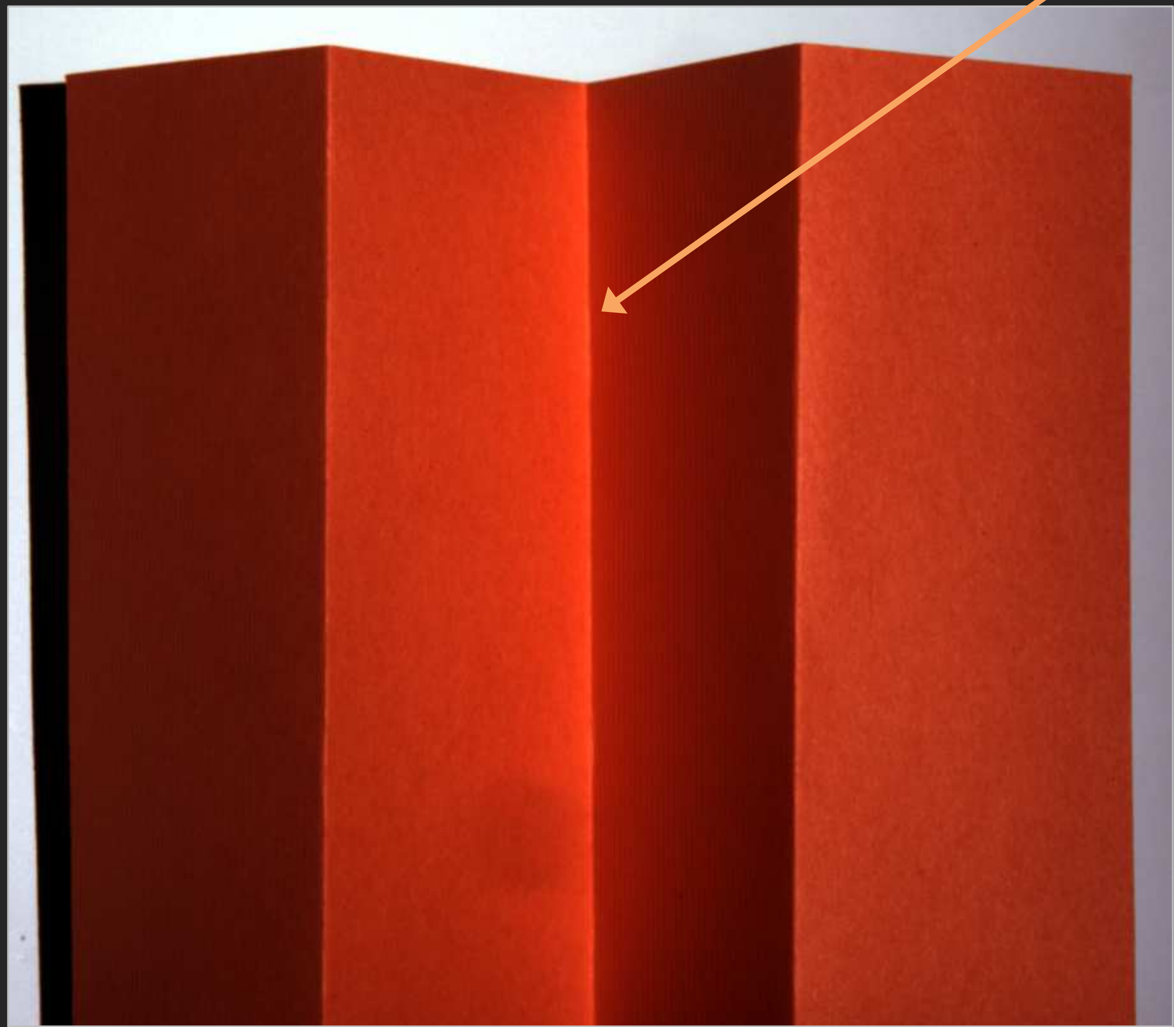
- Use only the direct component for shape estimation
- Several Issues
  - Estimating direct component is difficult
    - Requires lots of images
    - Global component depends on projected pattern for SL
  - SNR issues when direct component is small

Key Idea

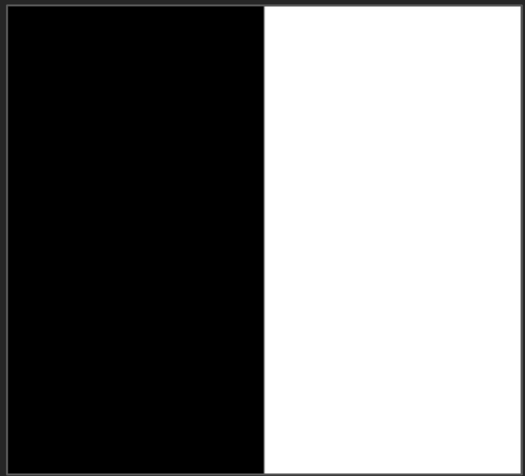
- Direct-Global separation is NOT required for Strutured Light (SL)
  - SL only require correct binarization of patterns
- Design patterns with appropriate spatial frequencies
  - Minimize the decoding errors
  - Correct errors using multiple sets of patterns

V-Groove Scene

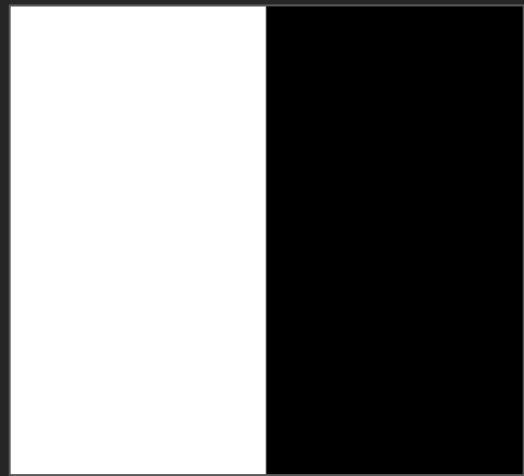
Inter-reflections



Conventional Gray codes

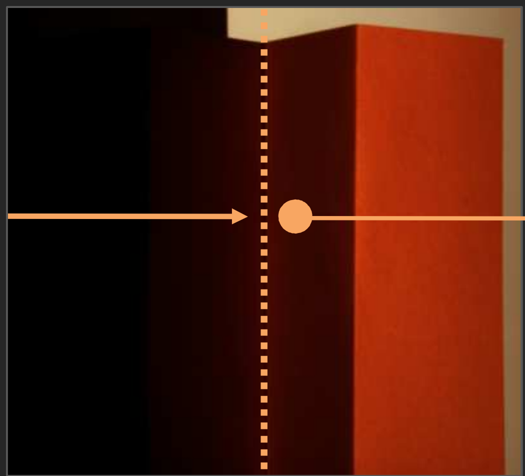


Low frequency pattern



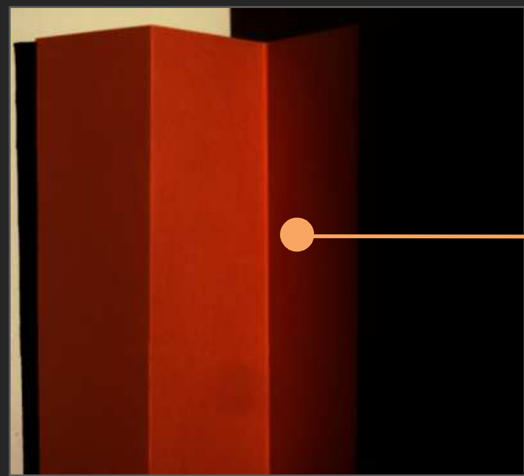
Inverse Pattern

Pattern Edge



$I = 0.16$

Captured Image

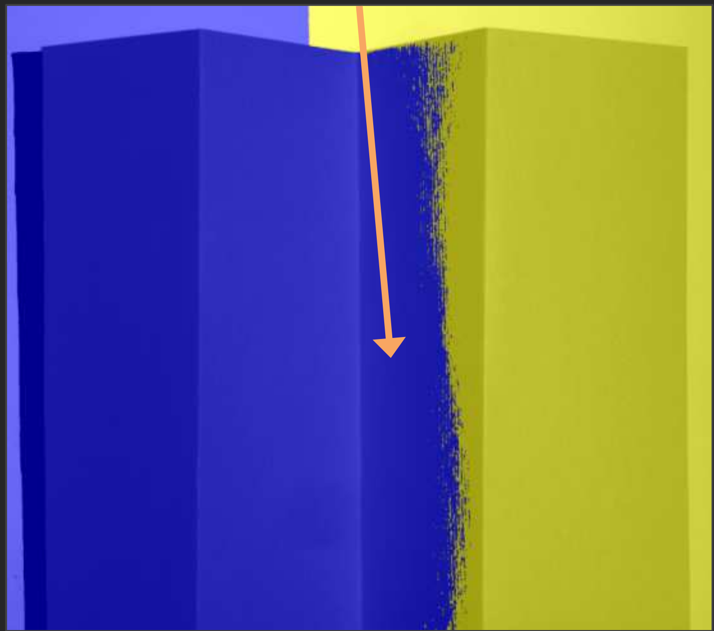


$\bar{I} = 0.25$

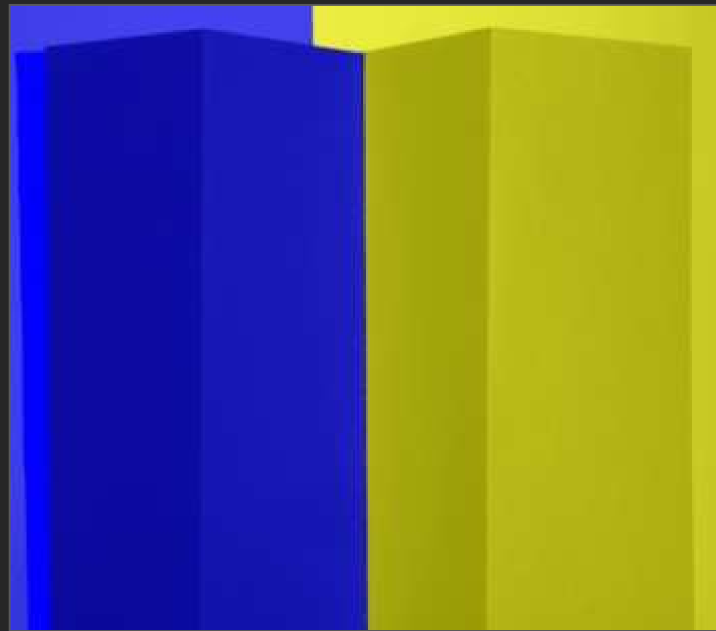
Captured Image

Binarization error

Errors due to inter-reflections



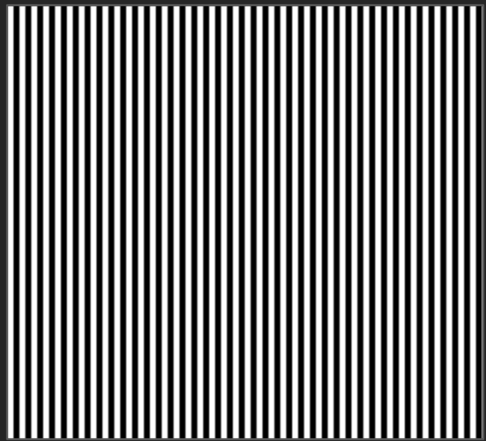
Incorrect Binarization



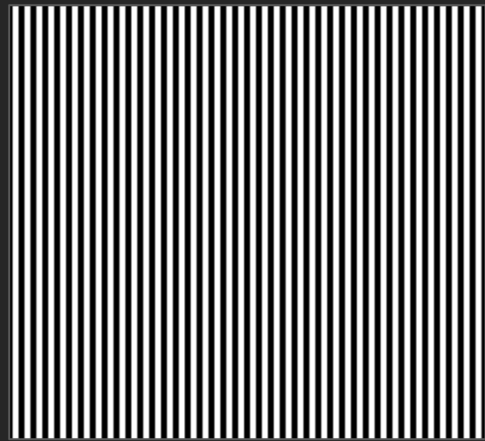
Ground-truth Binarization

One (illuminated) Zero (not-illuminated)

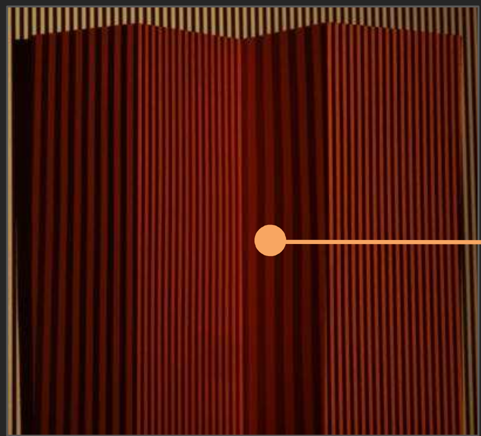
Binarization for high-frequency pattern



Pattern

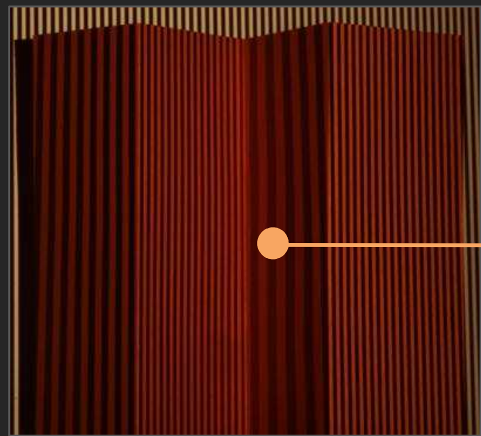


Inverse Pattern



Captured Image

$I = 0.25$

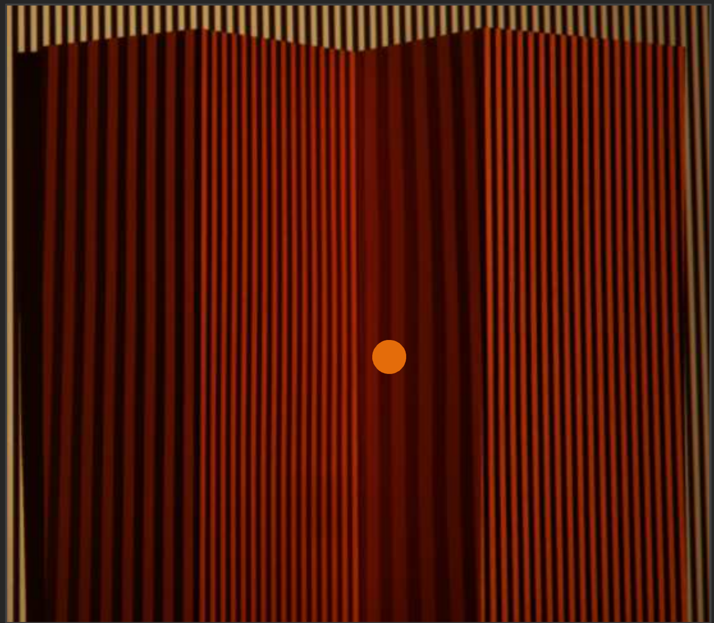


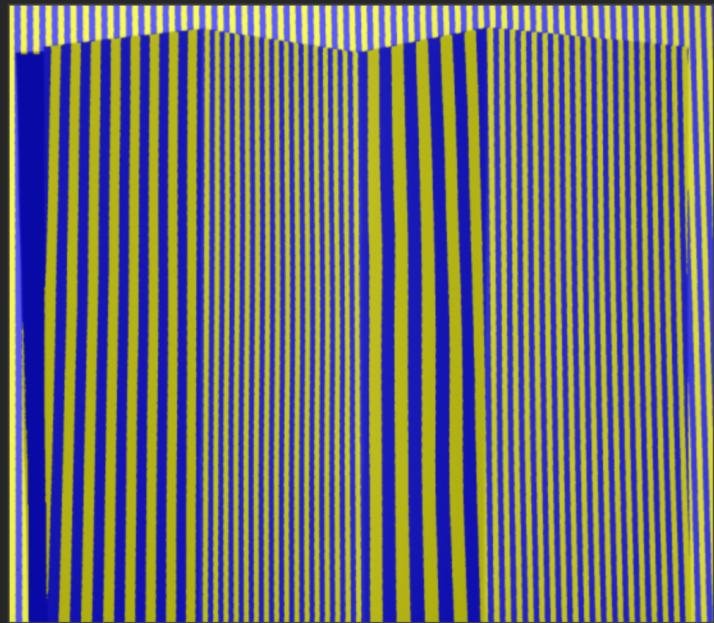
Captured Image

$\bar{I} = 0.16$

$$I = \text{Direct} + 0.5\ \text{Global} \quad > \quad \bar{I} = 0.5\ \text{Global}$$

High-frequency Patterns are Decoded Correctly

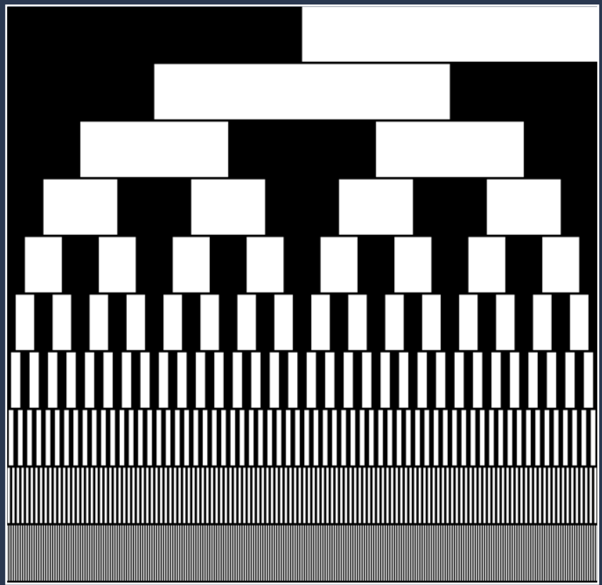

Captured Image


Binary Decoding

Require High Frequency Patterns for Inter-reflections

Structured Light Decoding

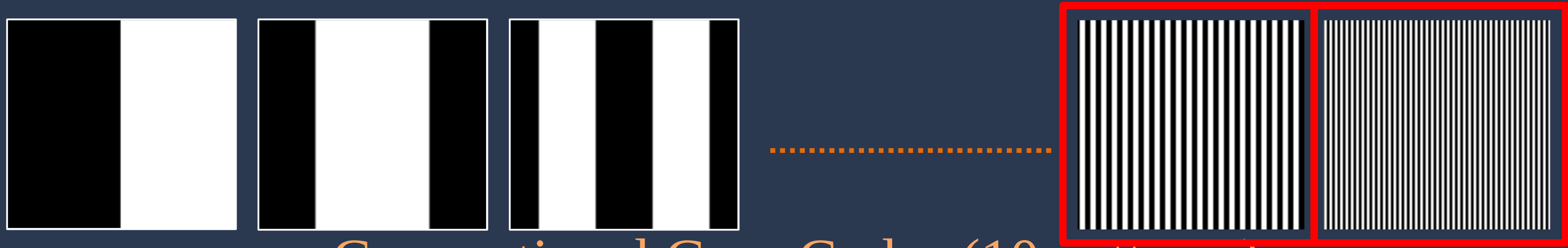
- Can we design decodable patterns with only high frequencies?
- Use XOR function
  - Invertible



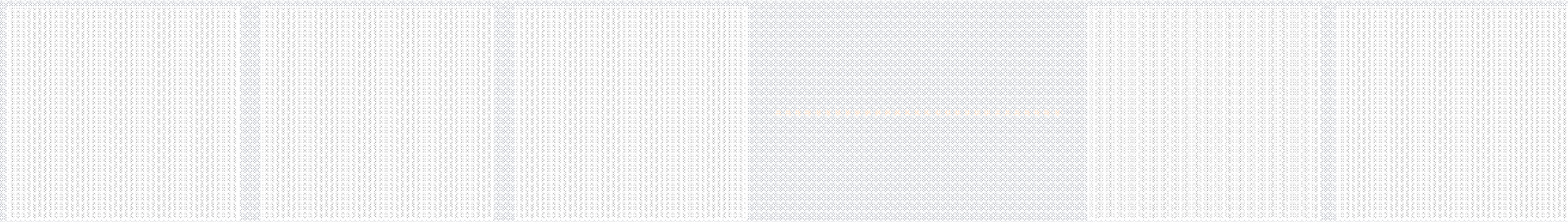
Conventional Gray Codes

Making the Logical XOR Codes

Base Plane Base Plane



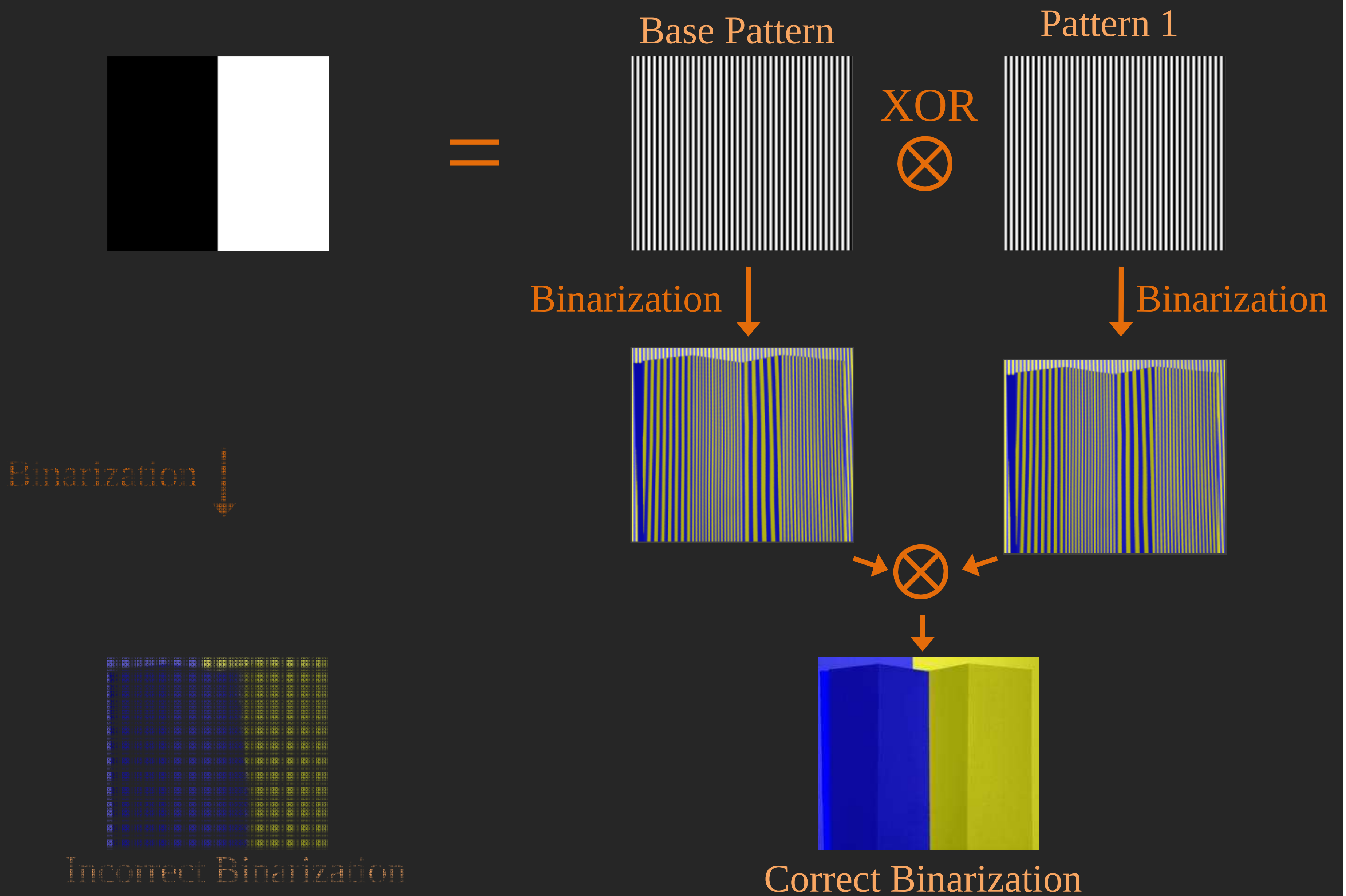
Conventional Gray Codes (10 patterns)



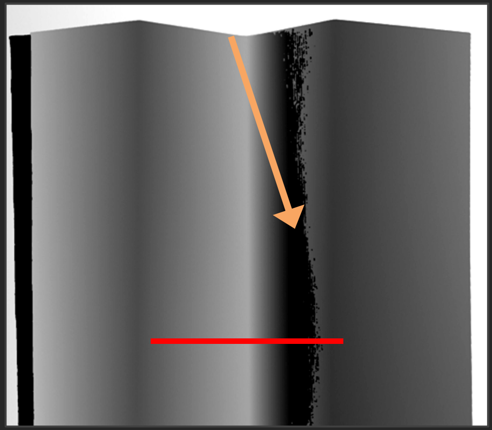
XOR of Last Pattern with Patterns 1-9 → *XOR-02* Codes (10 patterns)

XOR of Second-last Pattern with Patterns 1-8 → *XOR-04* Codes (10 patterns)

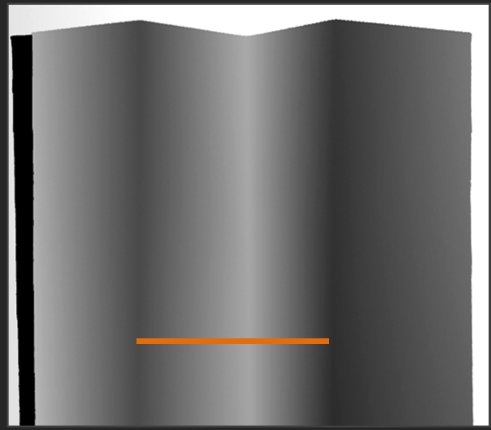
Logical Coding and Decoding



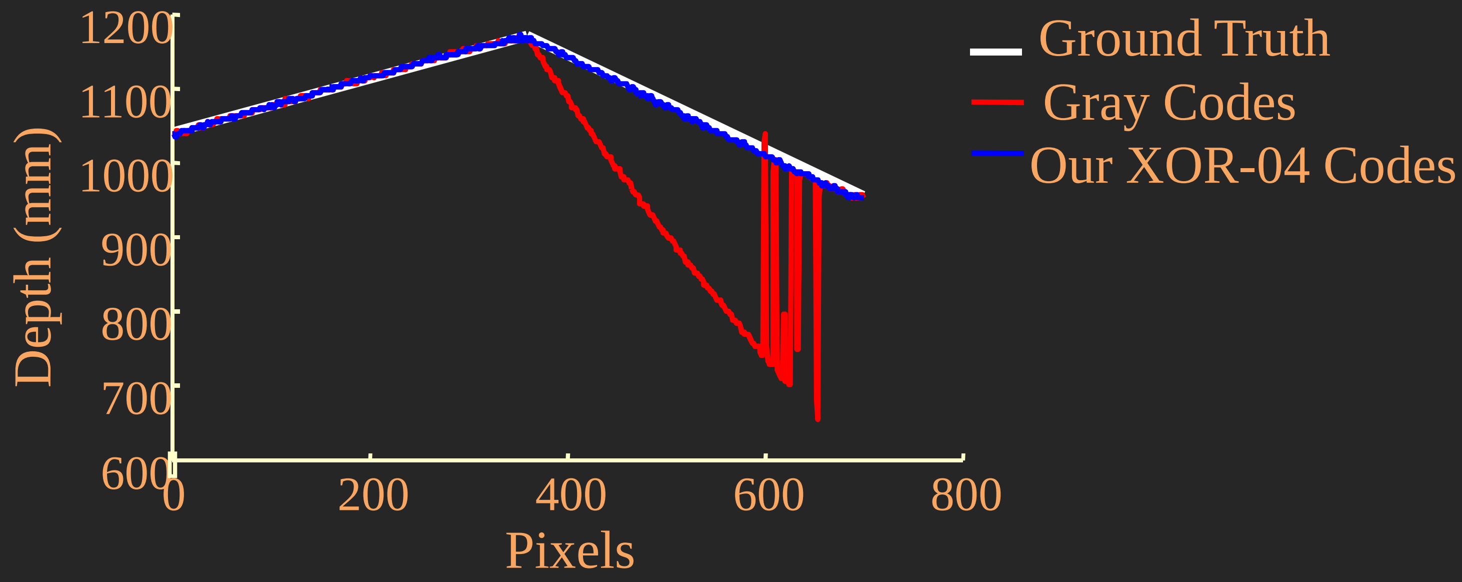
Depth Map Comparison



Conventional Gray Codes (11 images)

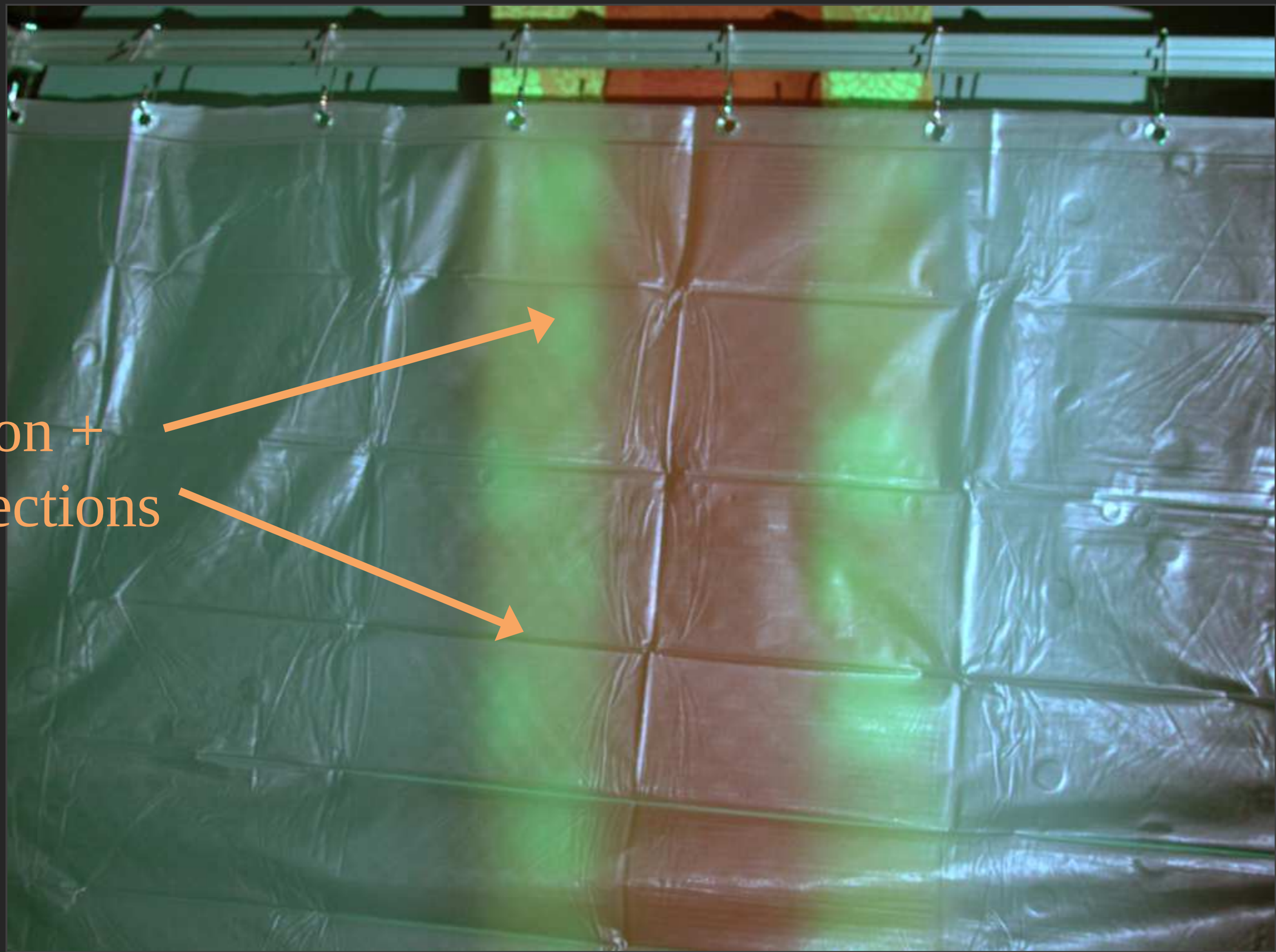


Our XOR-04 Codes (11 images)



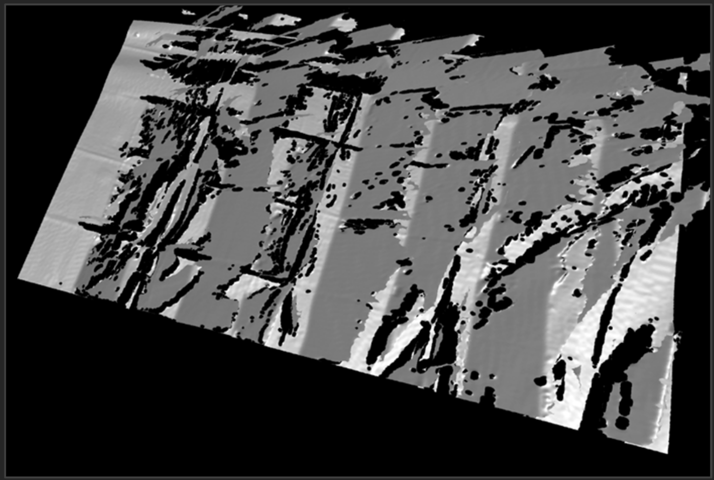
Shower Curtain

Diffusion +
Inter-reflections

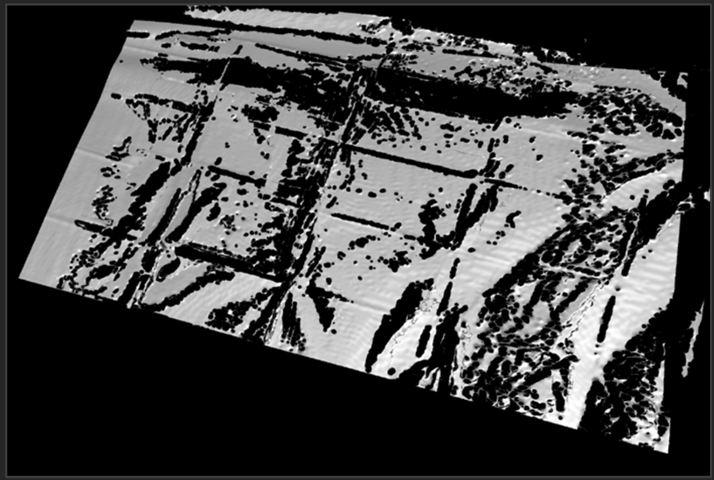


Goal is to reconstruct the shape of the shower-curtain. Shape of the curtain is planar because it was taped to the rod to avoid movement while capture.

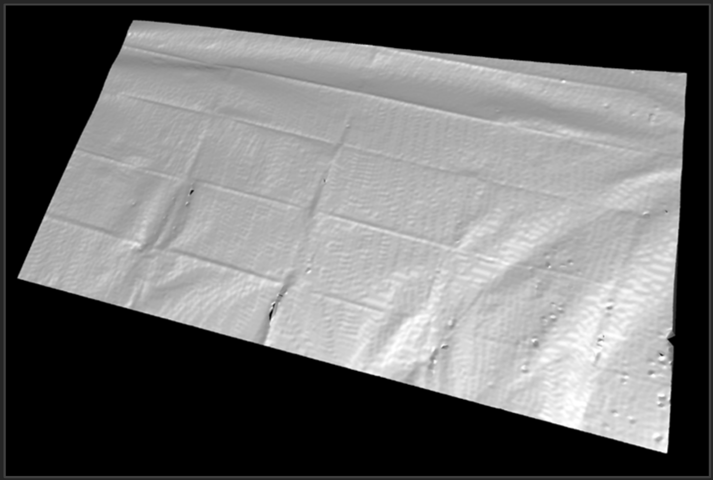
Shape Comparisons



Regular Gray Codes (11 images)

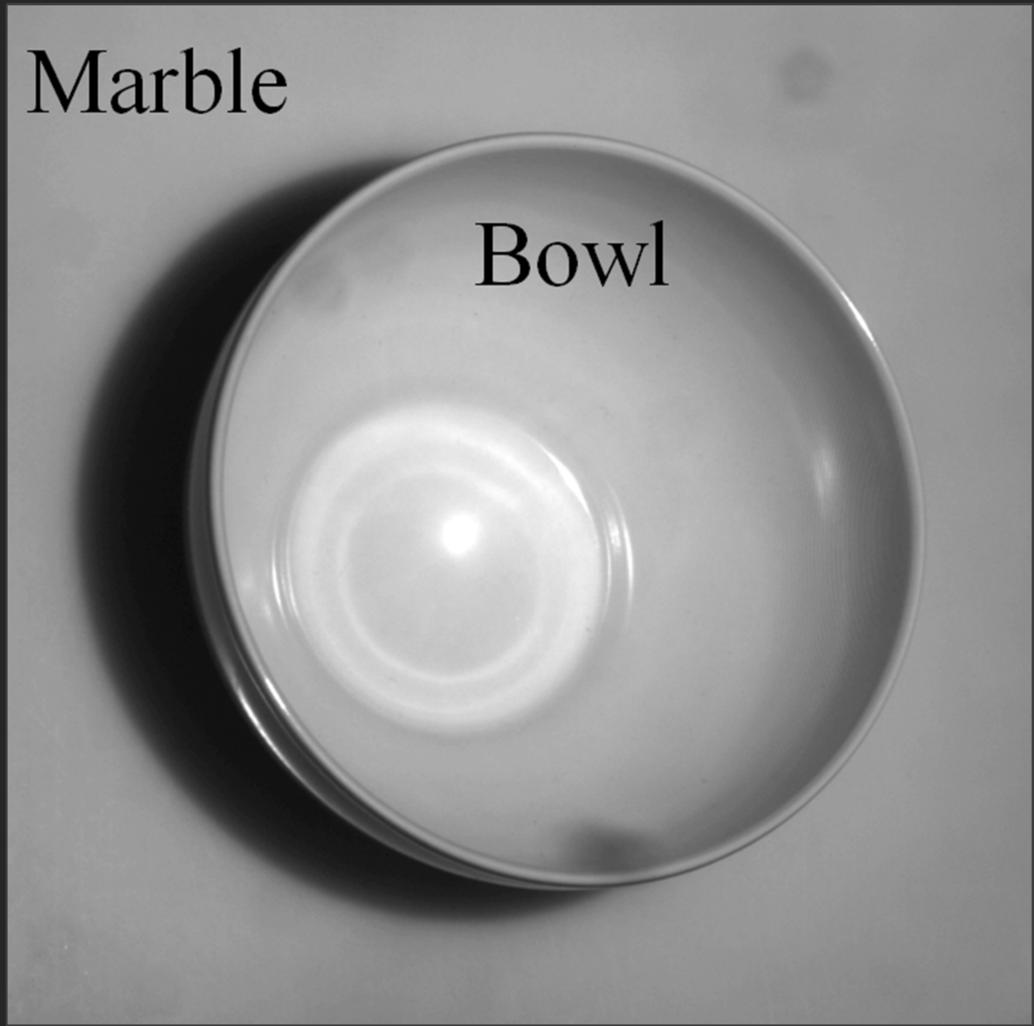


Phase-Shifting (18 images)



Our XOR Codes (11 images)

Bowl on a Marble Slab



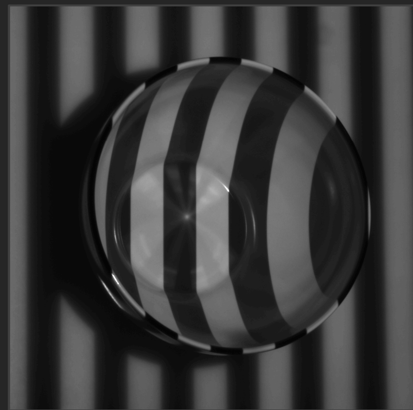
Captured images under conventional Gray codes

Lowest Frequency Illumination

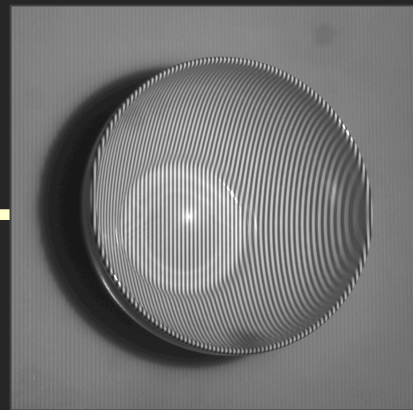
Highest Frequency Illumination

Pattern 1

Pattern 4



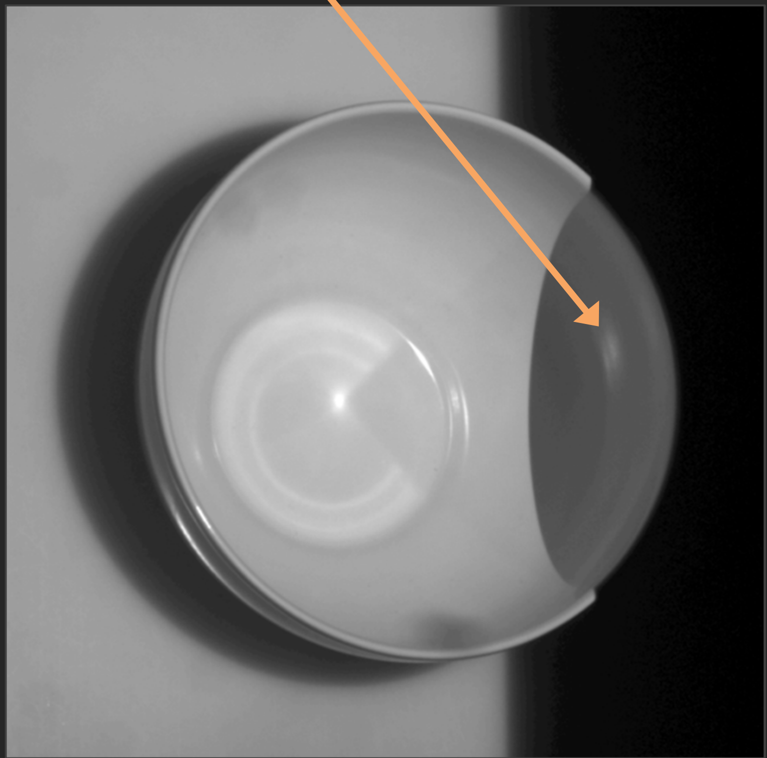
Pattern 7



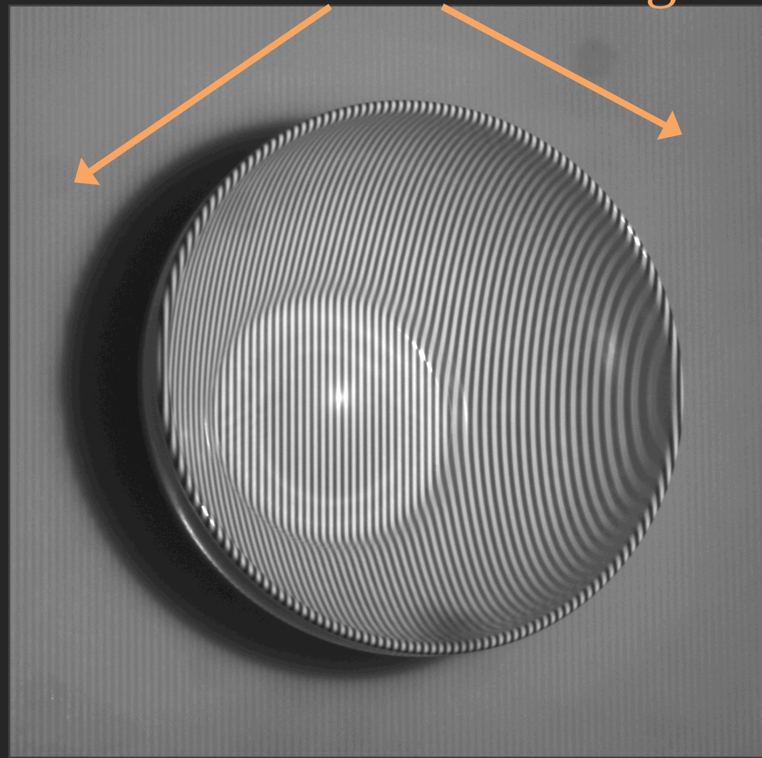
Pattern 10

Strong Inter-reflections

Blurring due to
Sub-surface Scattering



Low-frequency pattern

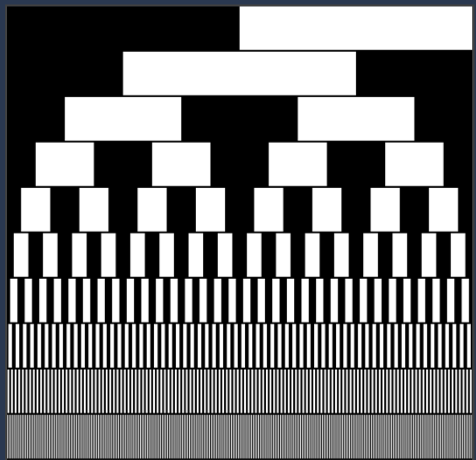


High-frequency pattern

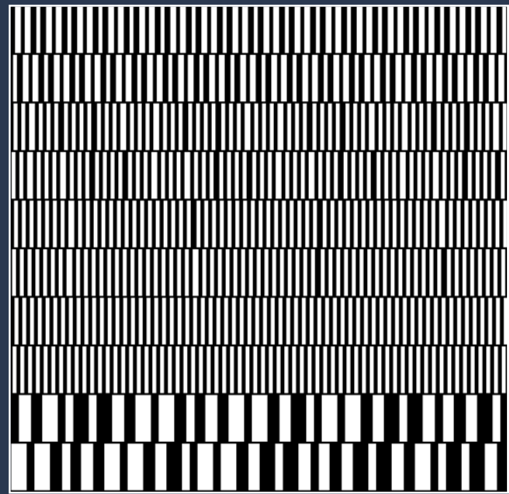
Require Low Frequency Patterns for Subsurface Scattering!!

Spatial Frequency of Patterns

- Conventional gray codes have both high frequency and low frequency patterns



Conventional GrayCodes



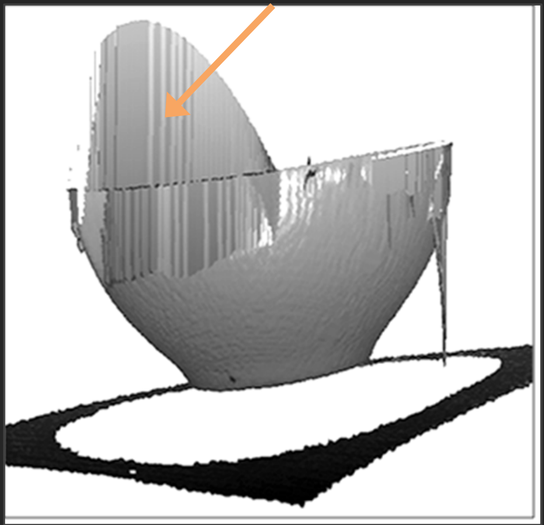
Max min-stripe-width Gray Code

- Can we design gray codes with minimal frequency variations?
  - Research problem in combinatorial algorithms
  - Several types of gray codes have been designed
  - E.g. balanced gray codes, maximum gap gray codes, non-composite gray codes etc

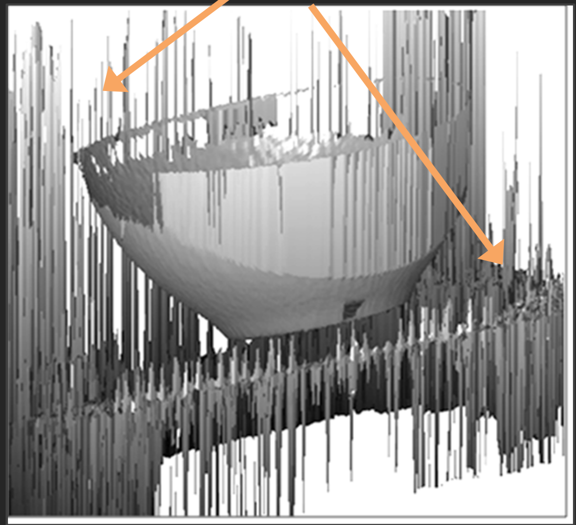
3D Visualizations

Errors due to Inter-reflections

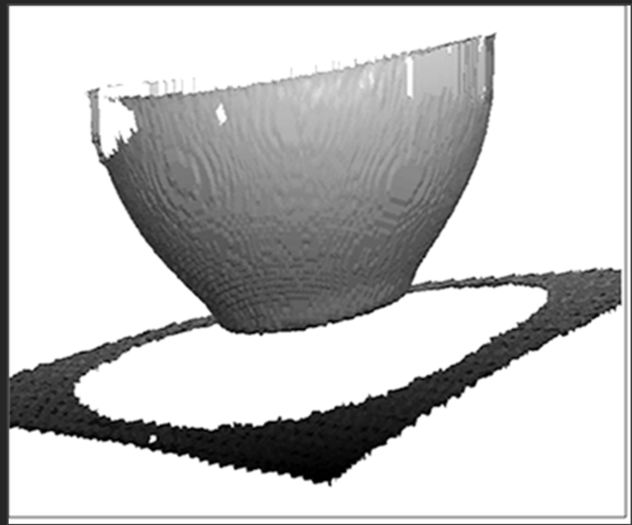
Errors due to sub-surface scattering



Conventional Gray

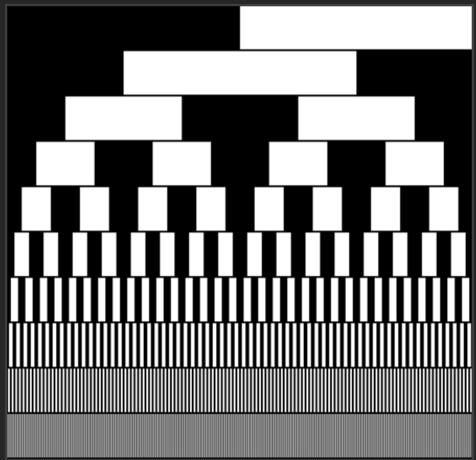


Modulated Phase-Shifting

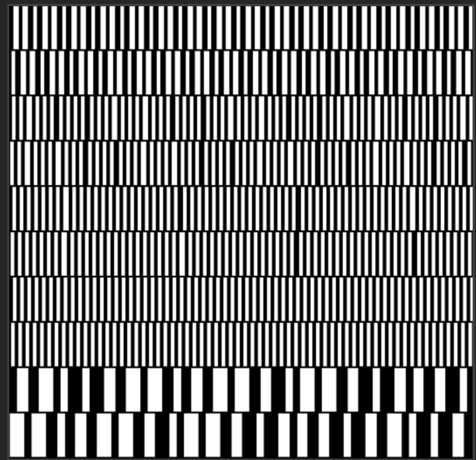


Our Technique

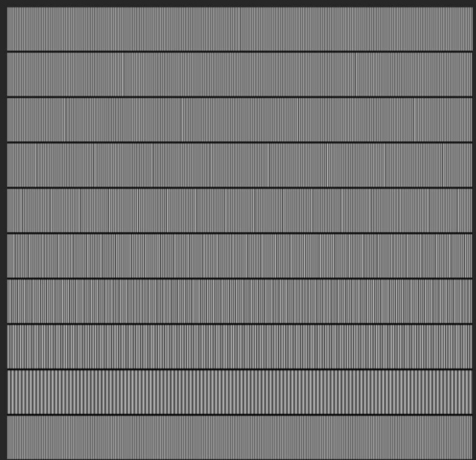
Ensemble of Codes for General Scenes



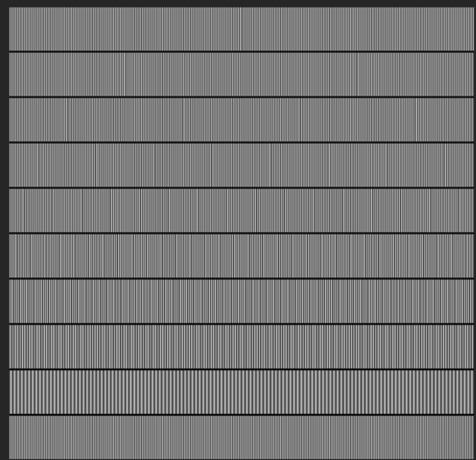
Conventional Gray (10 images)



Max min-SW Gray (10 images)

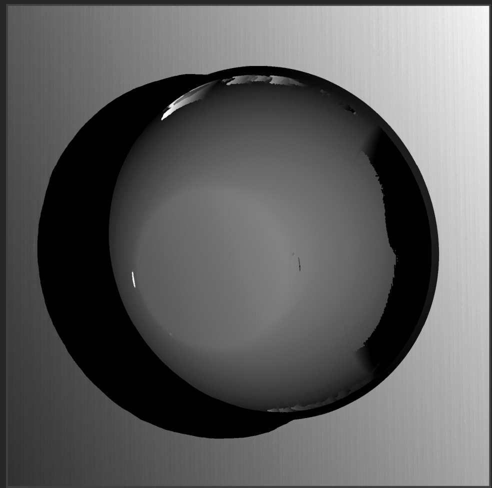


XOR-04 (10 images)



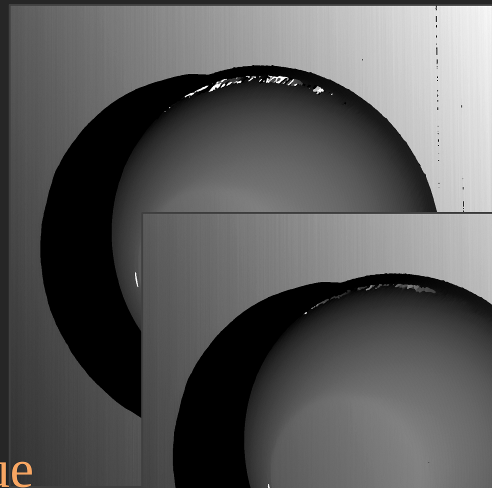
XOR-02 (10 images)

Ensemble of Codes for General Scenes

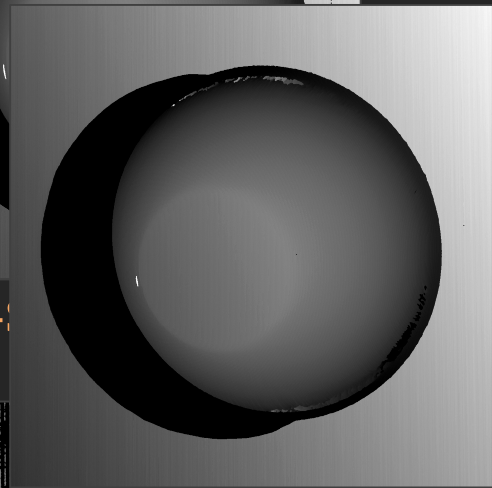


Conventional Gray (10 images)

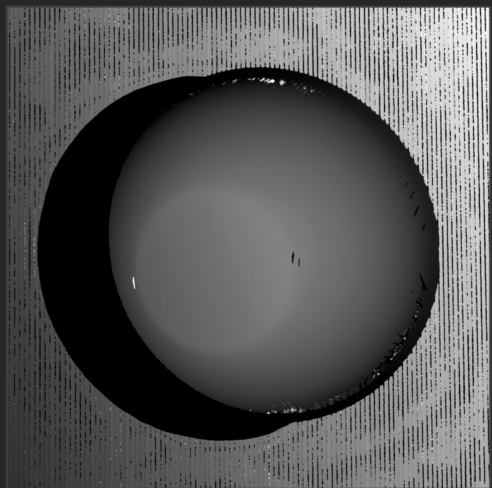
Return the consistent value



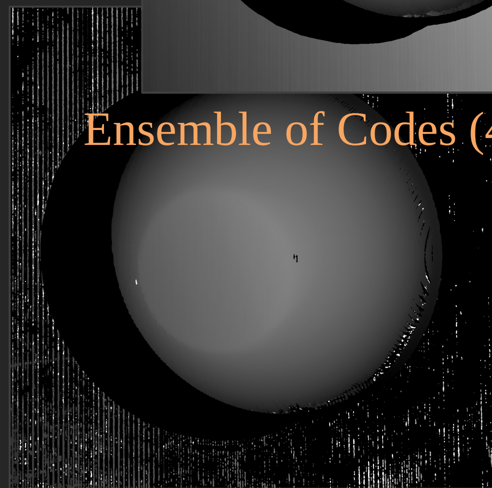
Max min-



Ensemble of Codes (41 images)

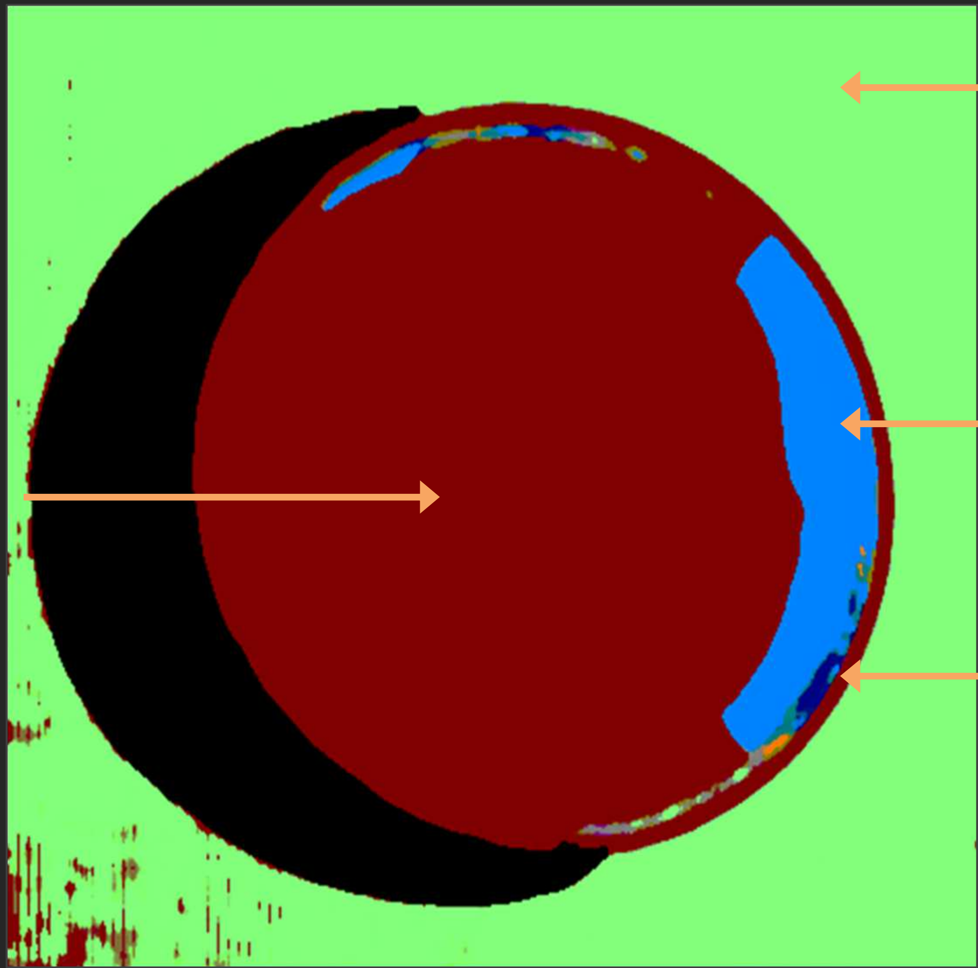


XOR-04 (10 images)



XOR-02 (10 images)

Qualitative Light Transport Analysis



All four codes agree

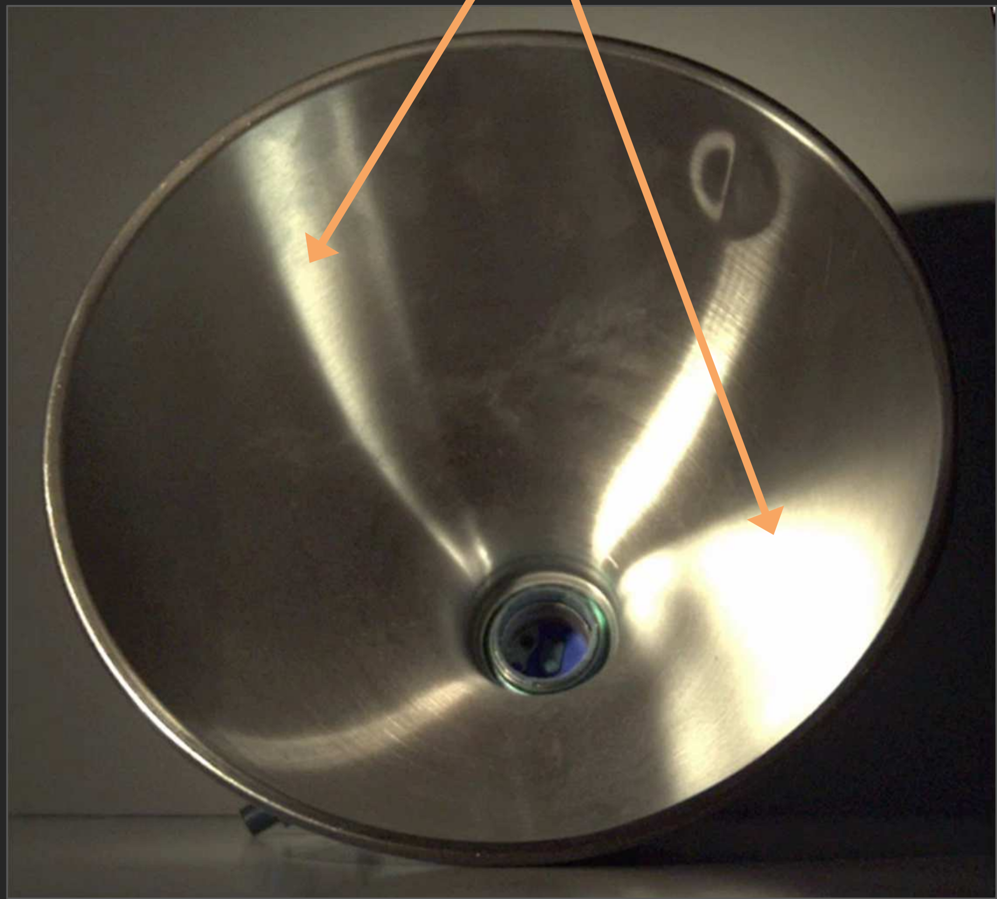
Sub-surface Scattering
(Both Gray codes agree)

Inter-reflections
(Both XOR codes agree)

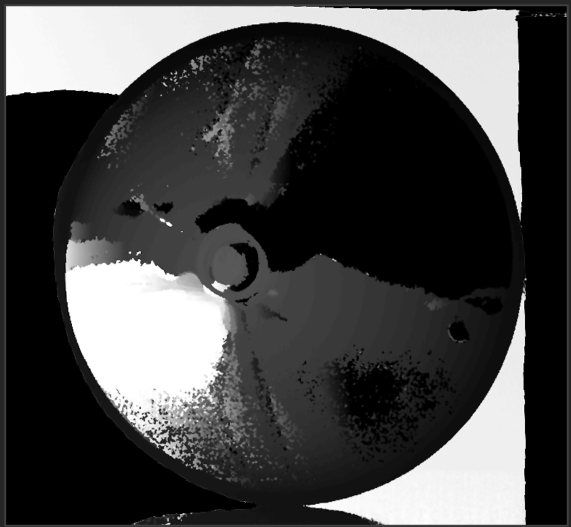
Error-Detection
(all four codes different)

Lamp made of shiny brushed metal

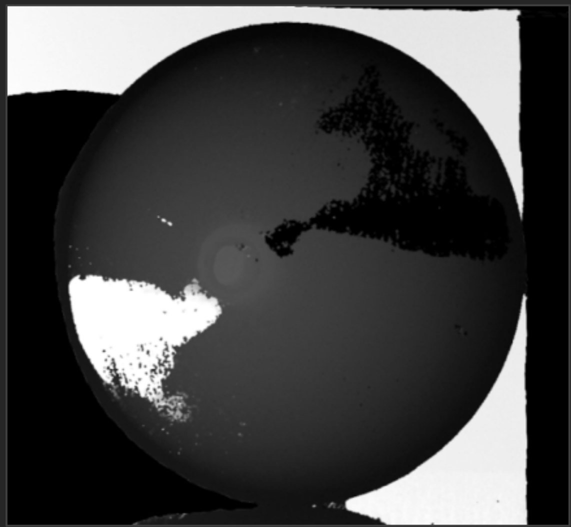
Strong and high-frequency inter-reflections



Depth Map Comparison



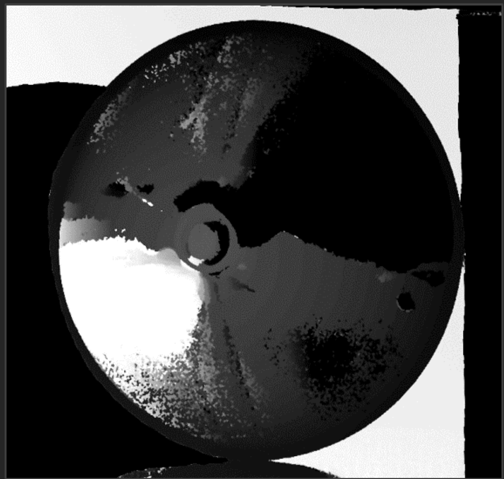
Regular Gray (11 images)



Our Ensemble Codes (41 images)

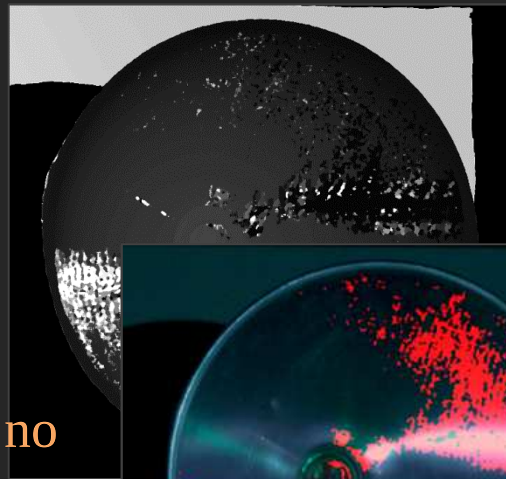
Error detection and correction

Error Detection using Consistency Check

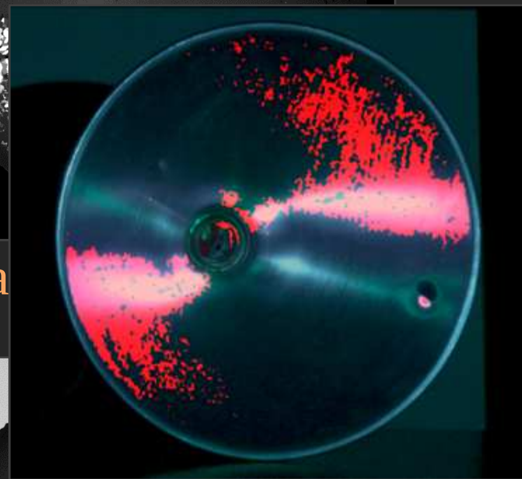


Conventional Gray

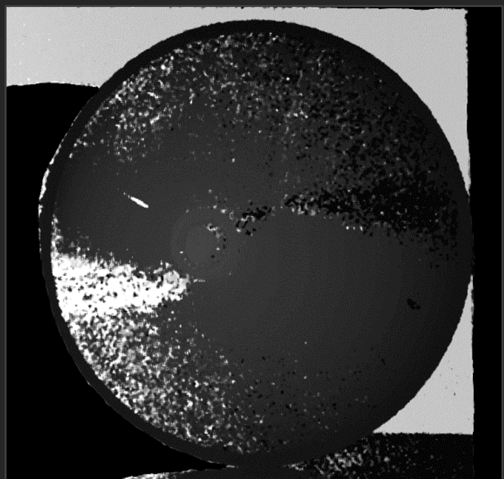
Declare error if no two codes agree



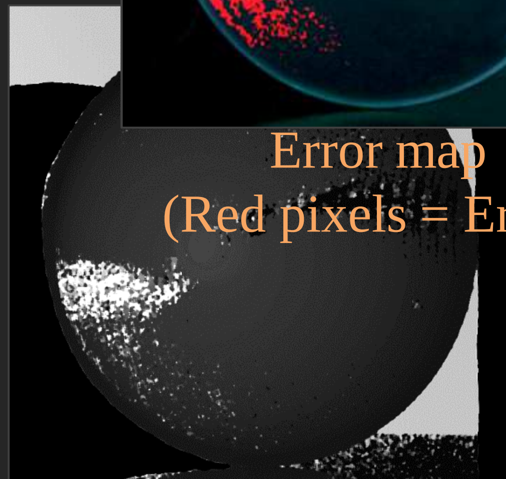
Ma



Error map
(Red pixels = Error)



XOR04

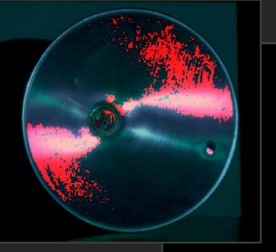


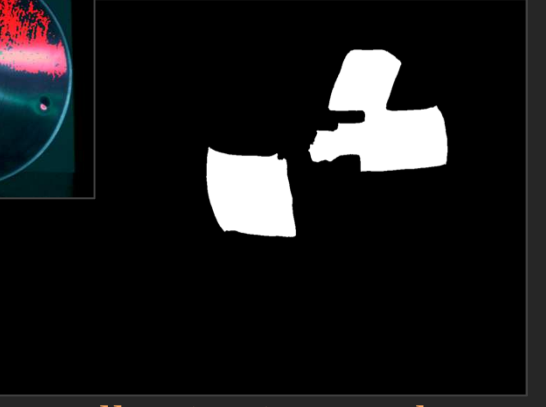
XOR02

Error Correction via Selective Illumination

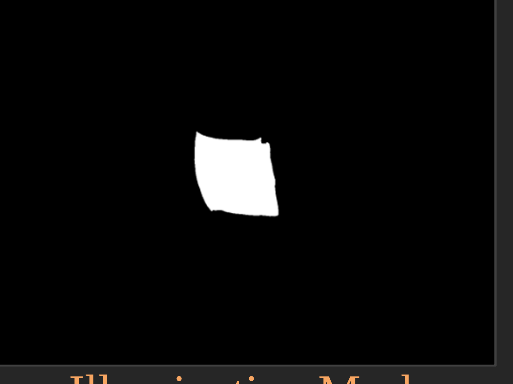
[Xu et al’ 2009]

Error map





Illumination Mask

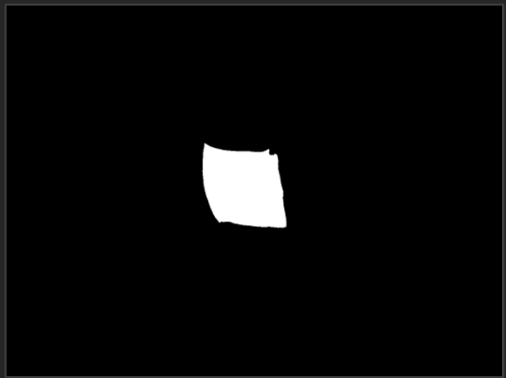


Illumination Mask
(Iteration 2)

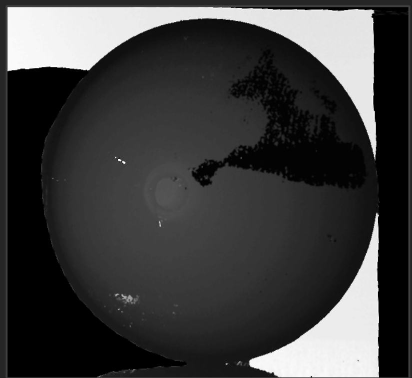
Illumination Mask
(Iteration 3)

Error Correction via Selective Illumination

Second Iteration (20 images)

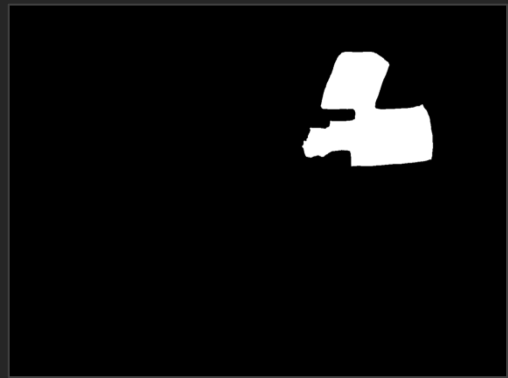


Illumination Mask

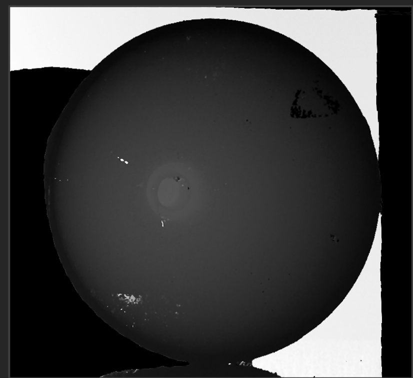


Depth Map (61 images)

Third Iteration (20 images)

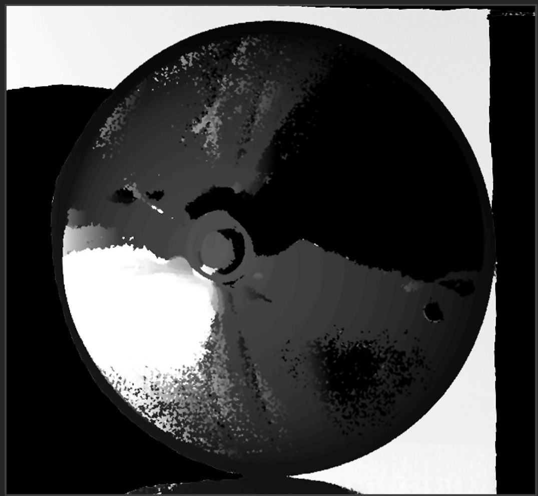


Illumination Mask

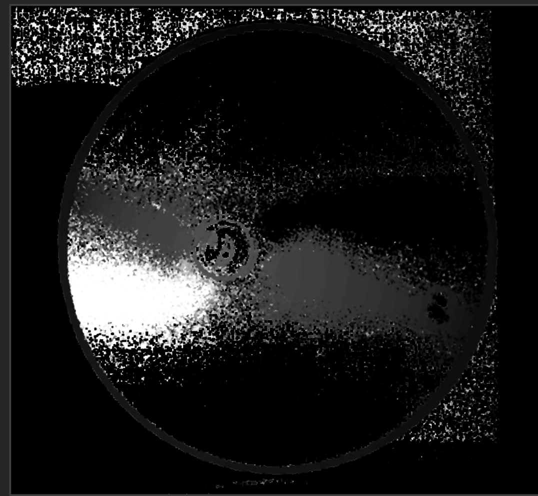


Depth Map (81 images)

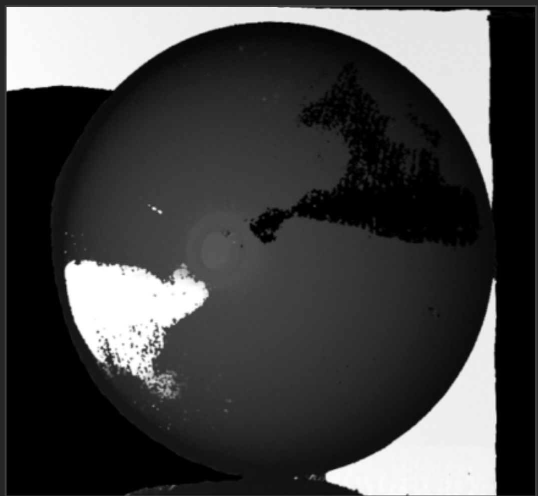
Depth Map Comparison



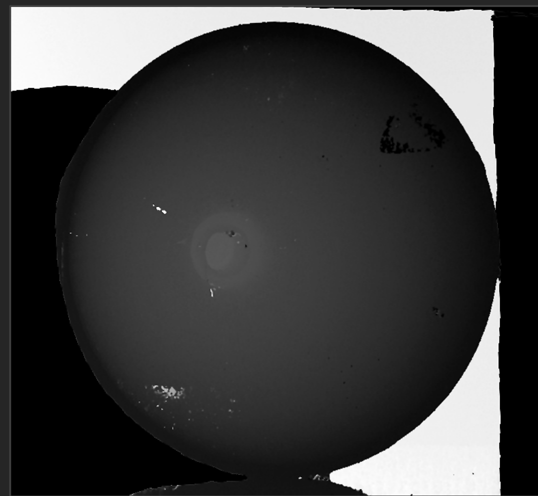
Regular Gray (11 images)



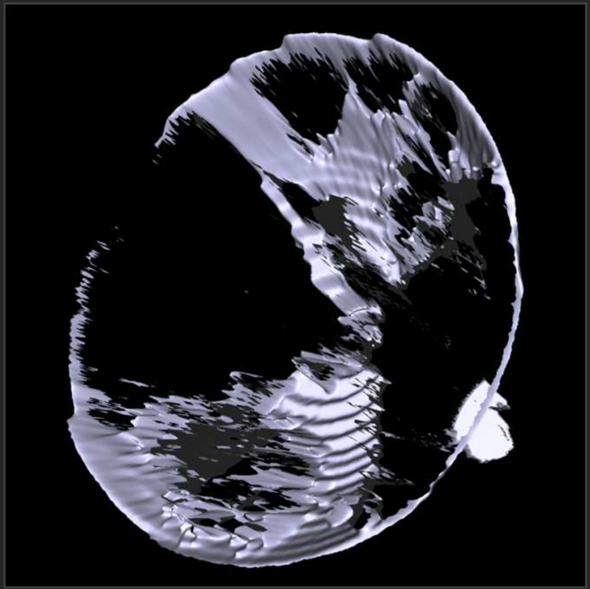
Modulated PS (162 images)



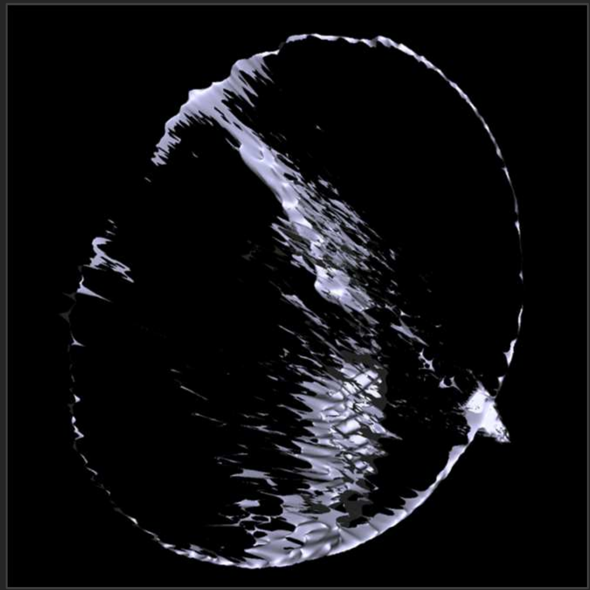
Our Ensemble Codes
(41 images)



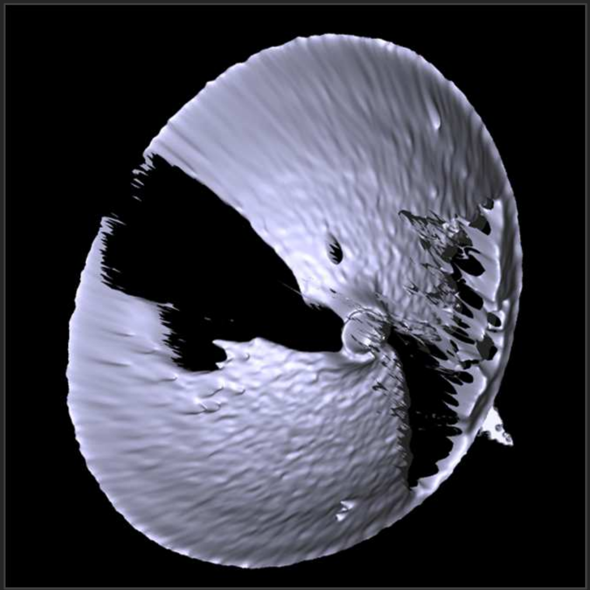
Error Correction: 2 extra
iterations (81 images)



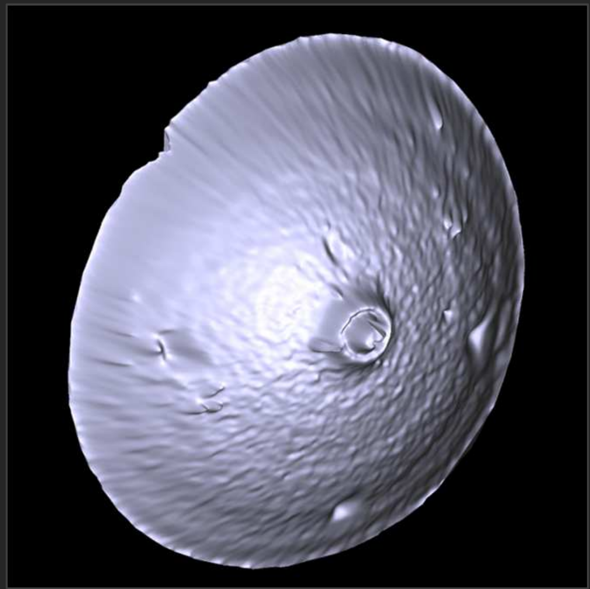
Regular Gray (11 images)



Modulated PS (162 images)



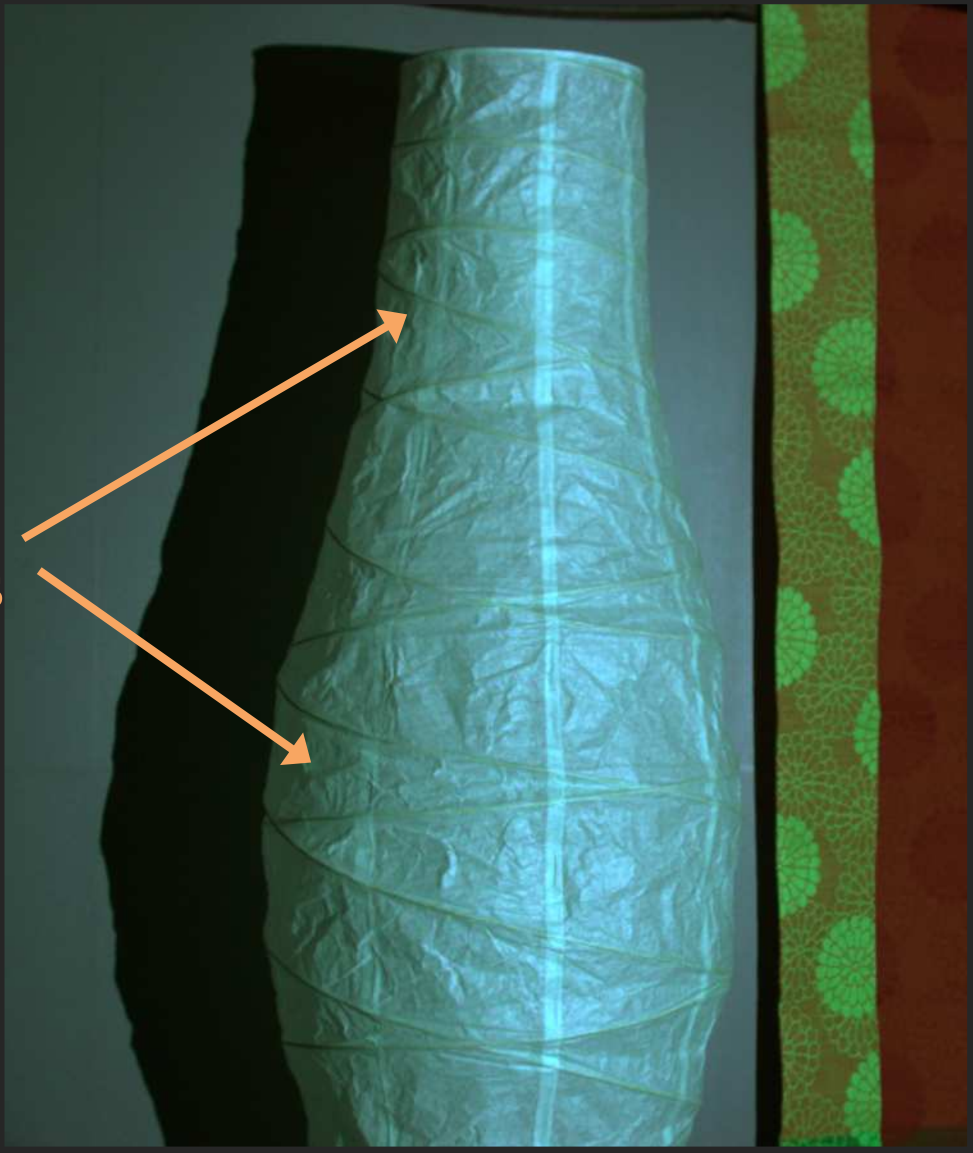
Ensemble Codes
(41 images)



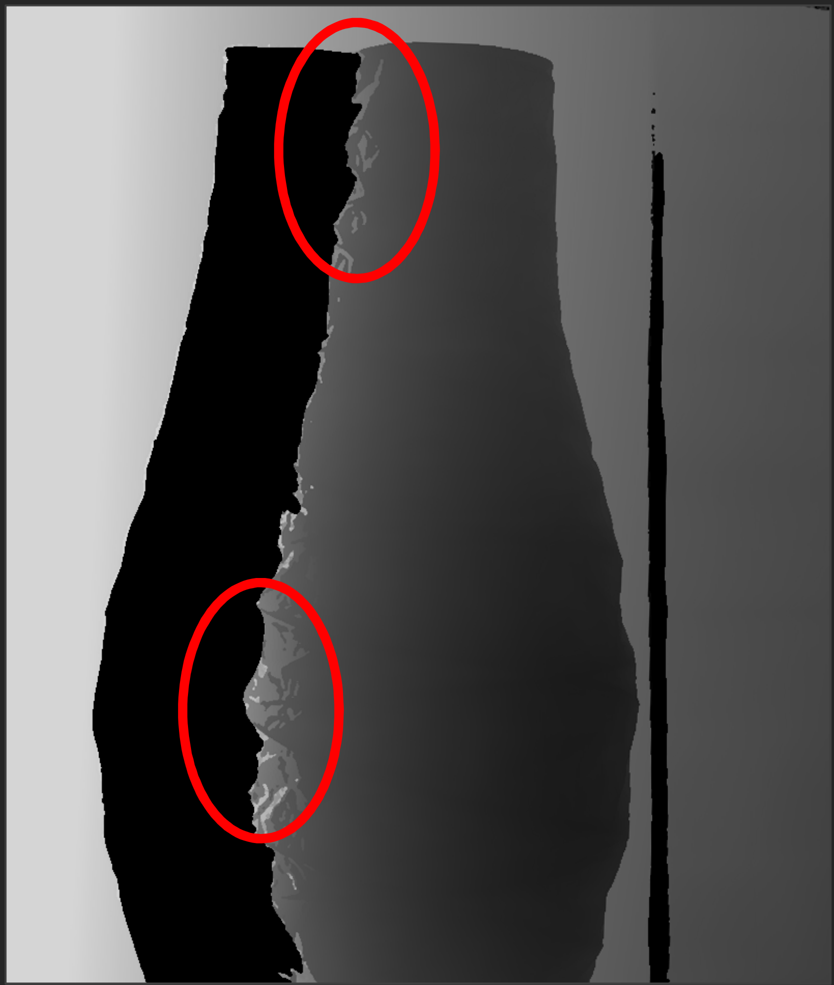
Error Correction: 2 extra
iterations (81 images)

Ikea Lamp

Diffusion +
Inter-reflections



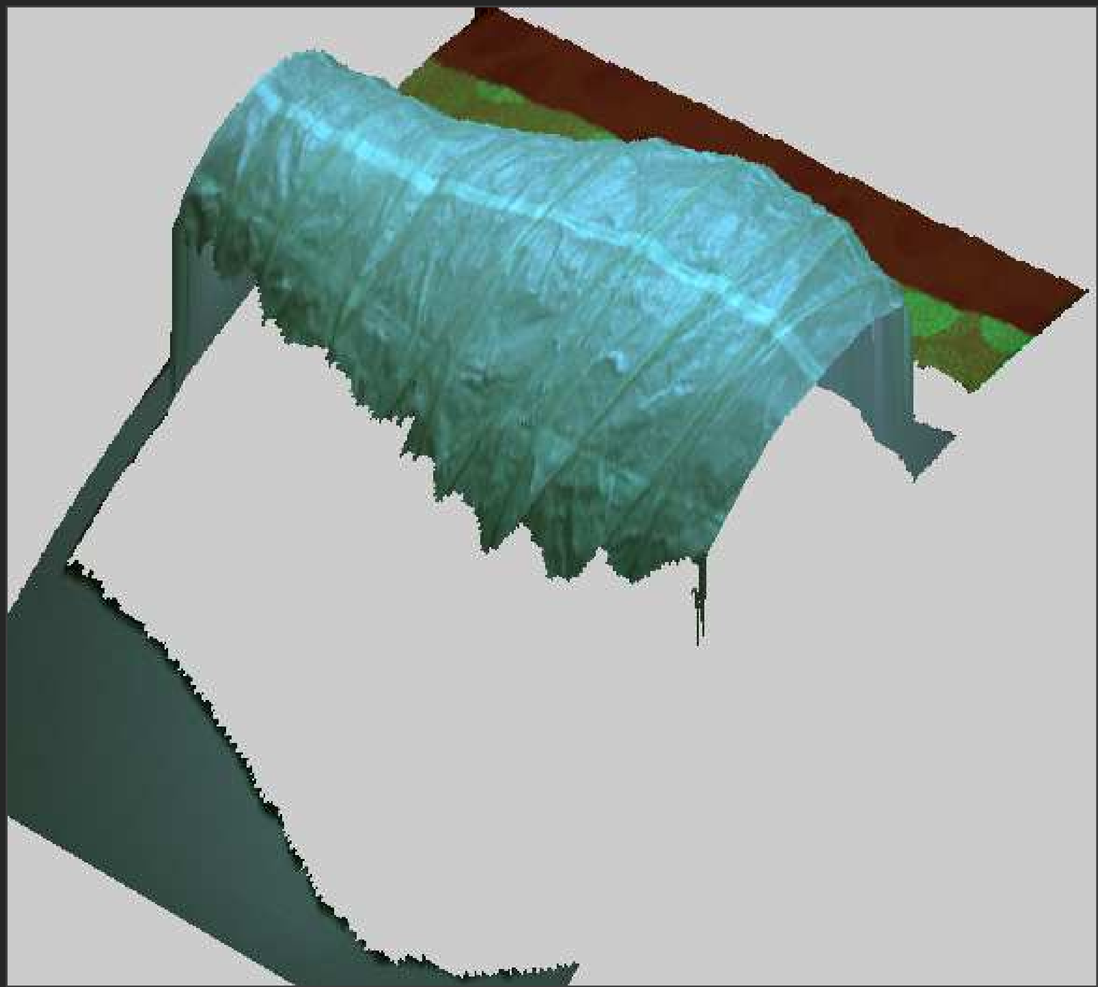
Depth-Map Comparison



Regular Gray Codes (11 images)

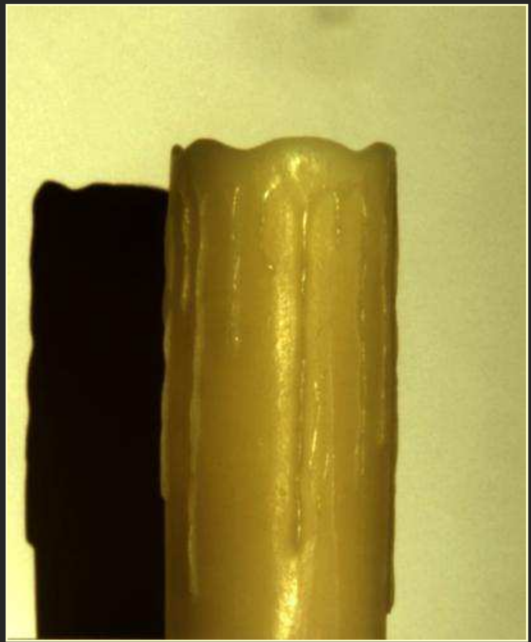
Our Ensemble Codes (41 images)

3D Visualization using our ensemble codes

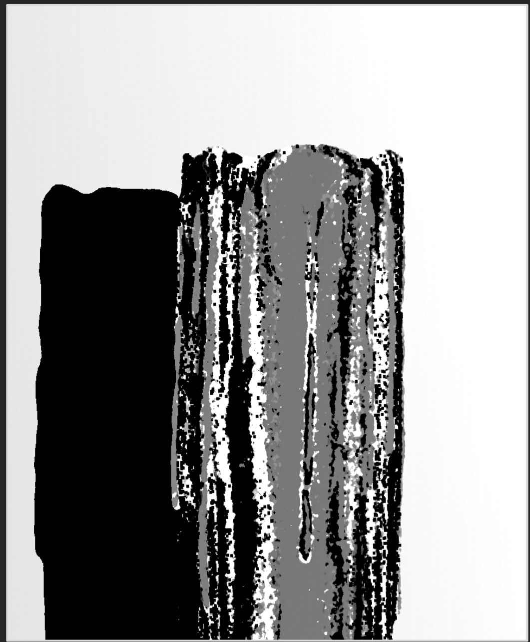


Translucent Wax Candle

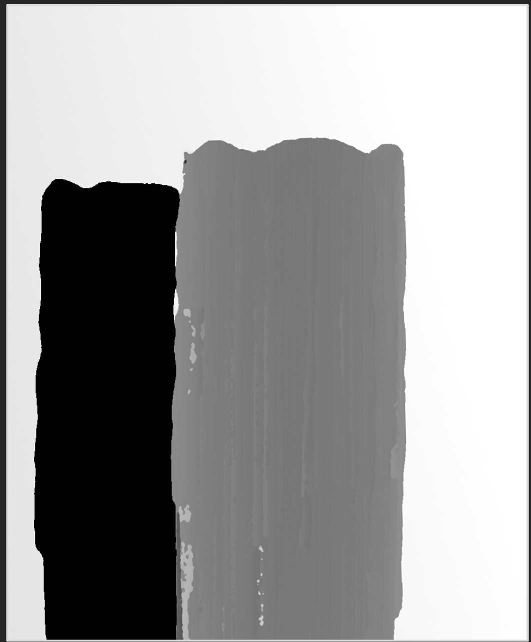
Errors due to strong sub-surface scattering



Scene



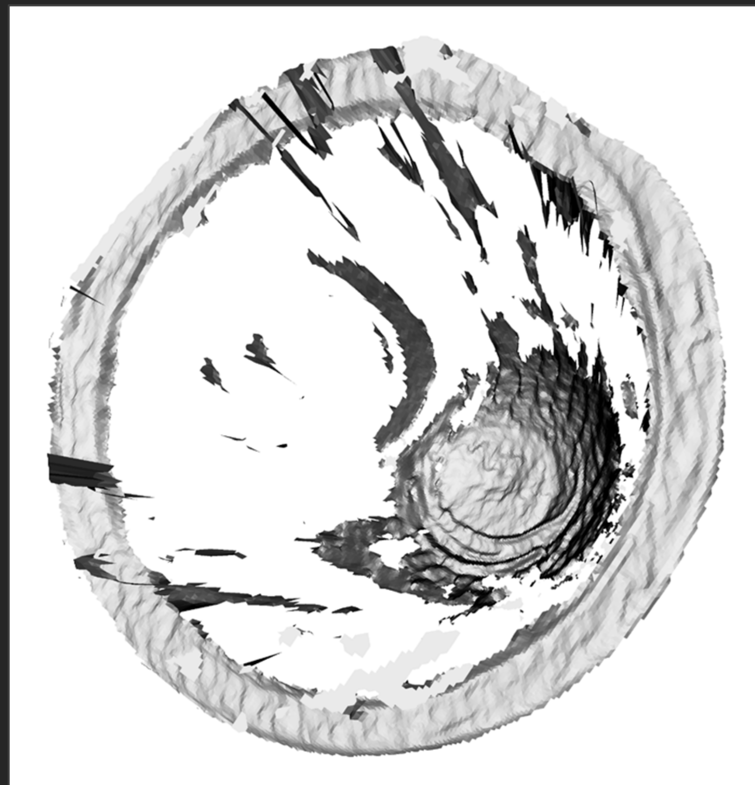
Modulated Phase-Shifting (162 images)



Our Ensemble Codes (41 images)

Multiple Global Illumination Effects

Deep Wax Container



Shape Using Ensemble Codes

Structured Light under Global Illumination

- Direct-Global Separation is NOT required
- Design patterns with appropriate spatial frequencies
  - Minimize the decoding errors
  - Correct errors using multiple sets of patterns

Computational Cameras and Illumination

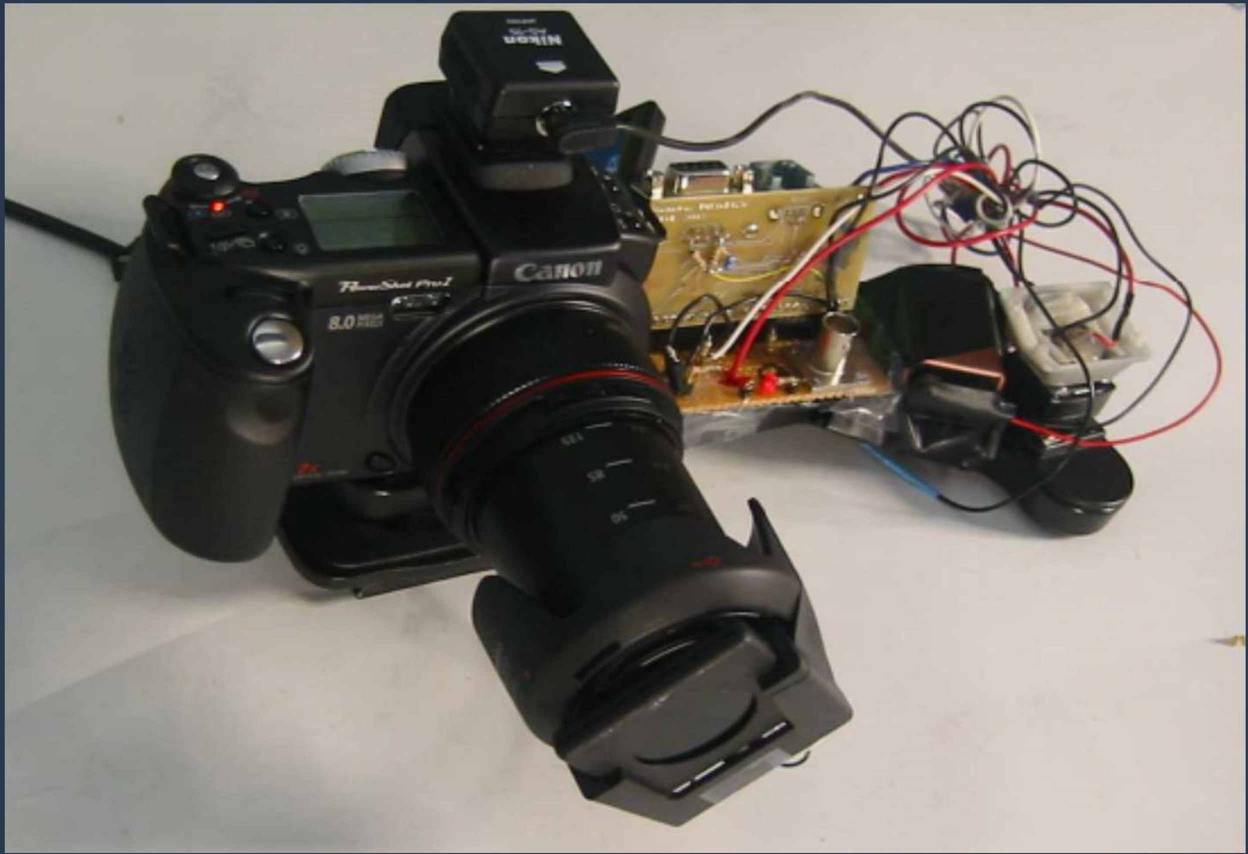
- Computational Illumination (Projector)
  - Structure Light
  - Design of new codes
  - Global Illumination

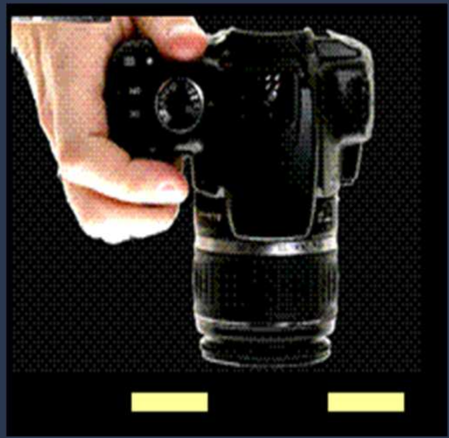
- Computational Cameras
  - Motion Blur, Focus Blur, Light Fields, Plenoptic Function

Coded Exposure [Raskar, Agrawal, Tumblin SIGGRAPH 2006]

Coded Exposure (Flutter Shutter) Camera

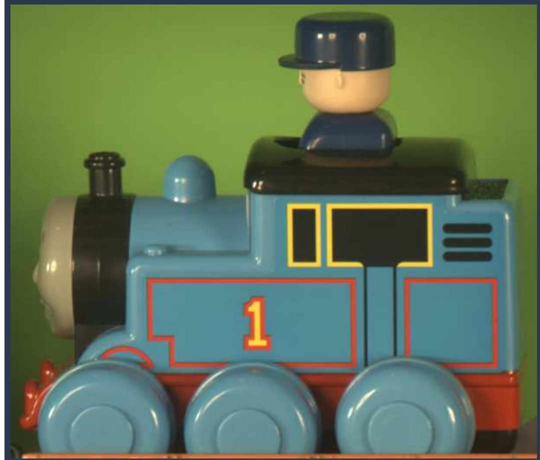
Raskar, Agrawal, Tumblin [Siggraph2006]



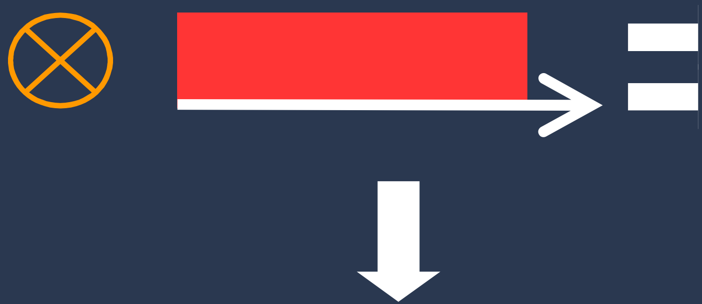


Coding in Time: Shutter is opened and closed

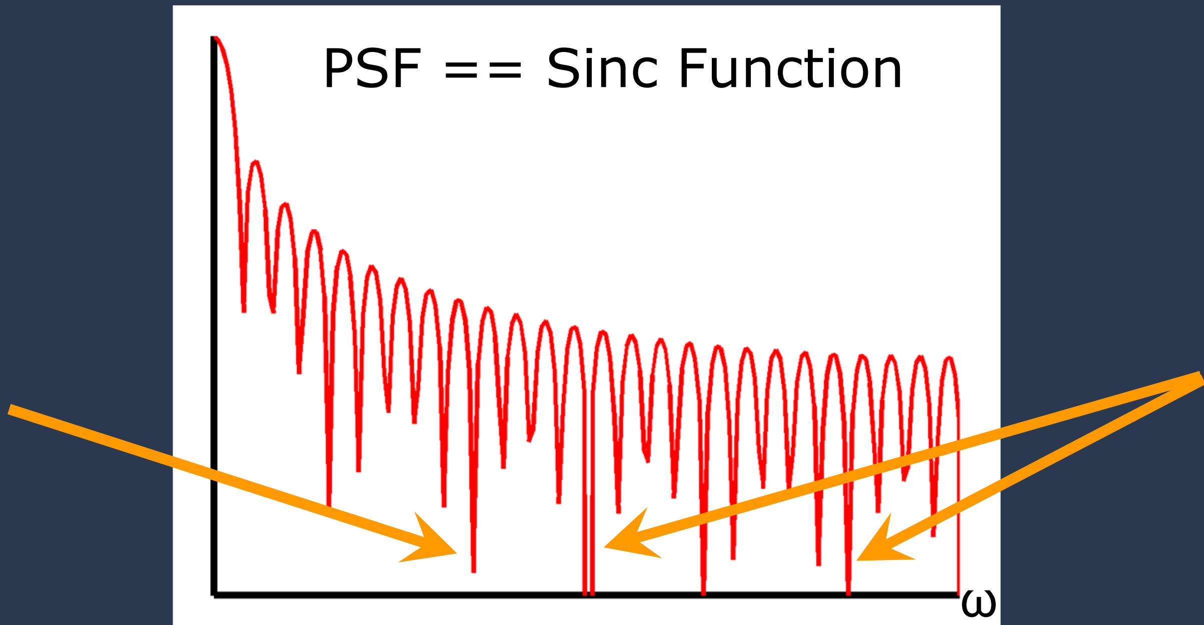
Blurring == Convolution



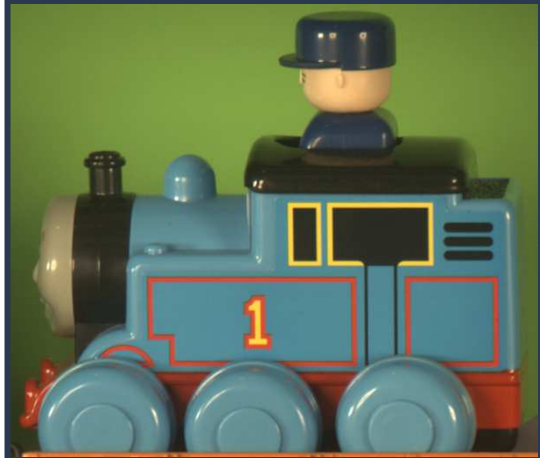
Sharp Photo



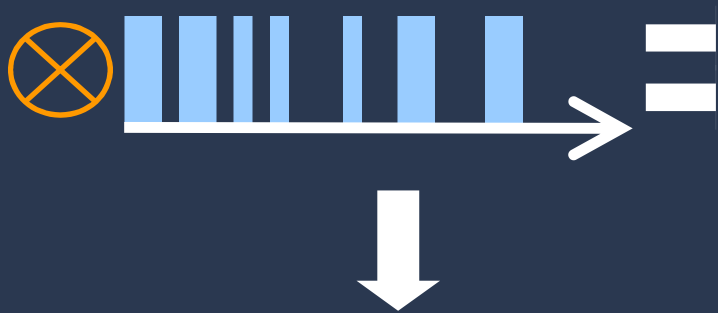
Blurred Photo

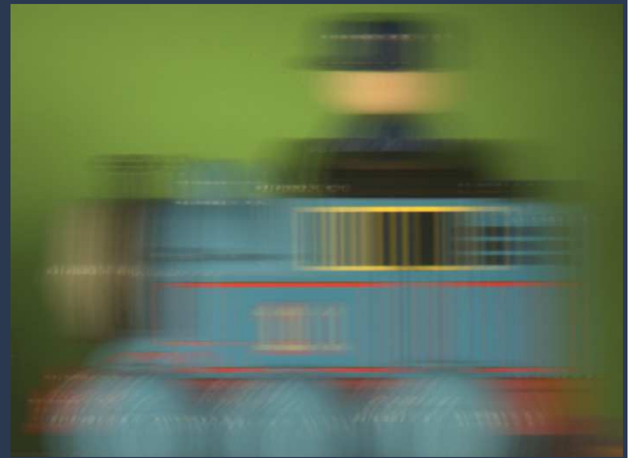


Traditional Camera: Shutter is OPEN: Box Filter

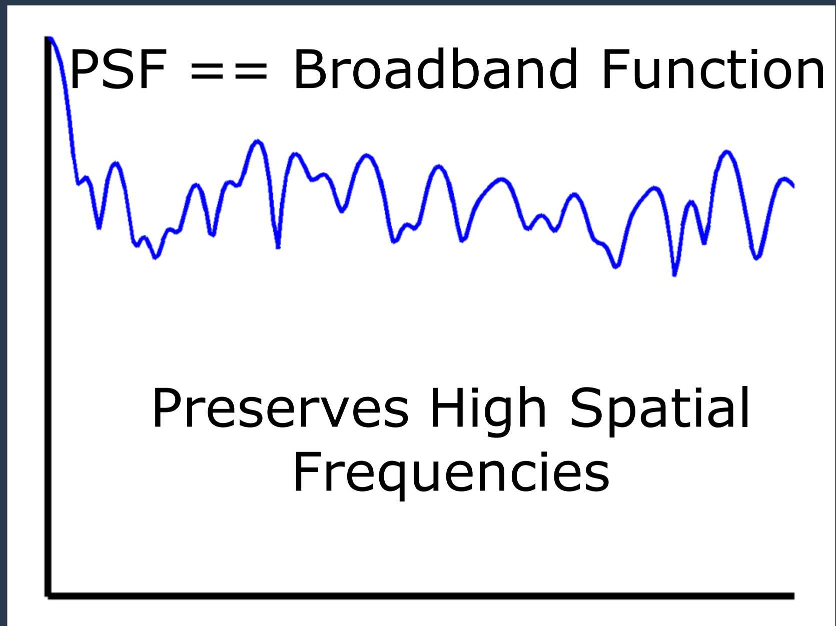


Sharp Photo

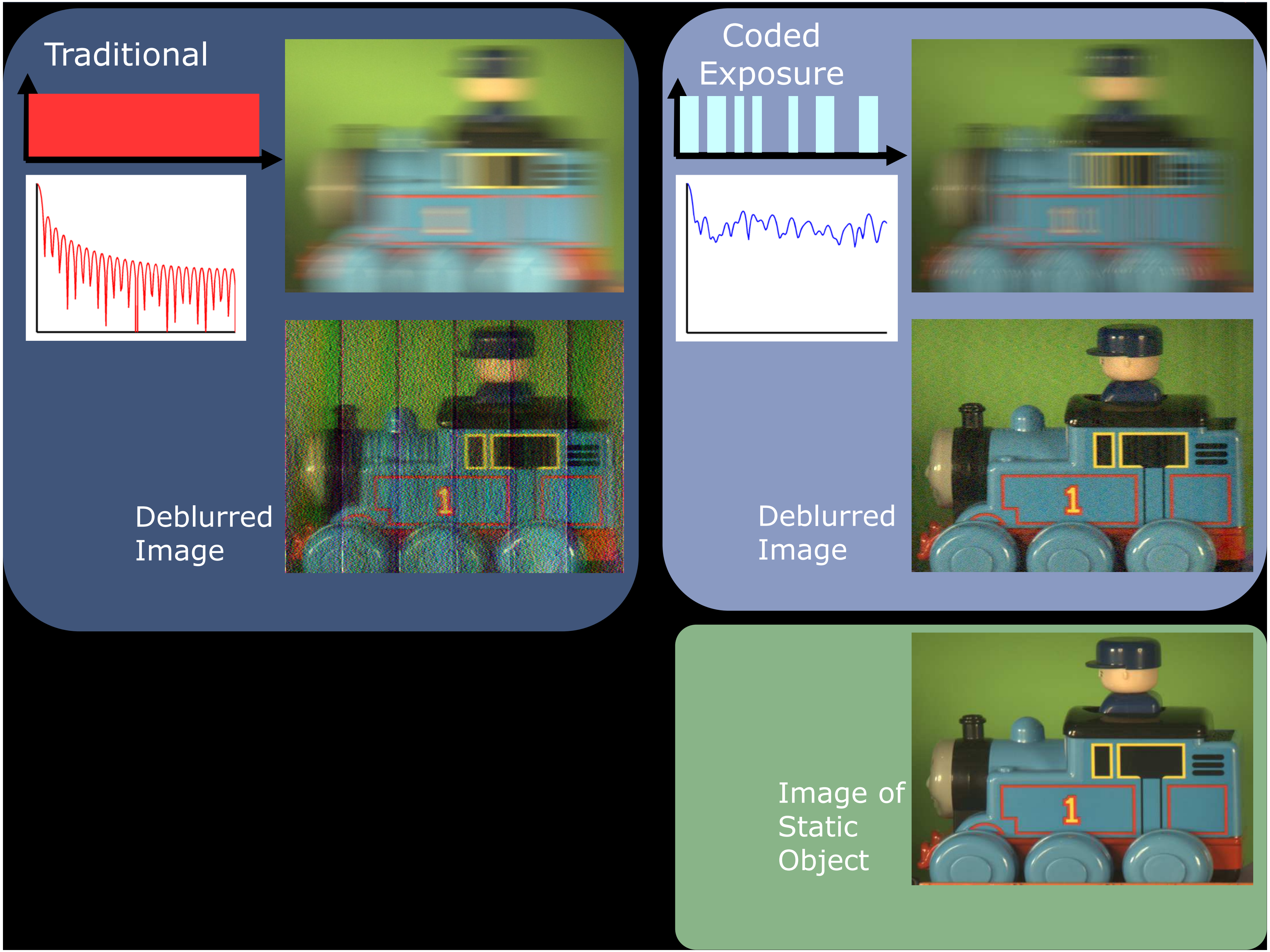




Blurred Photo



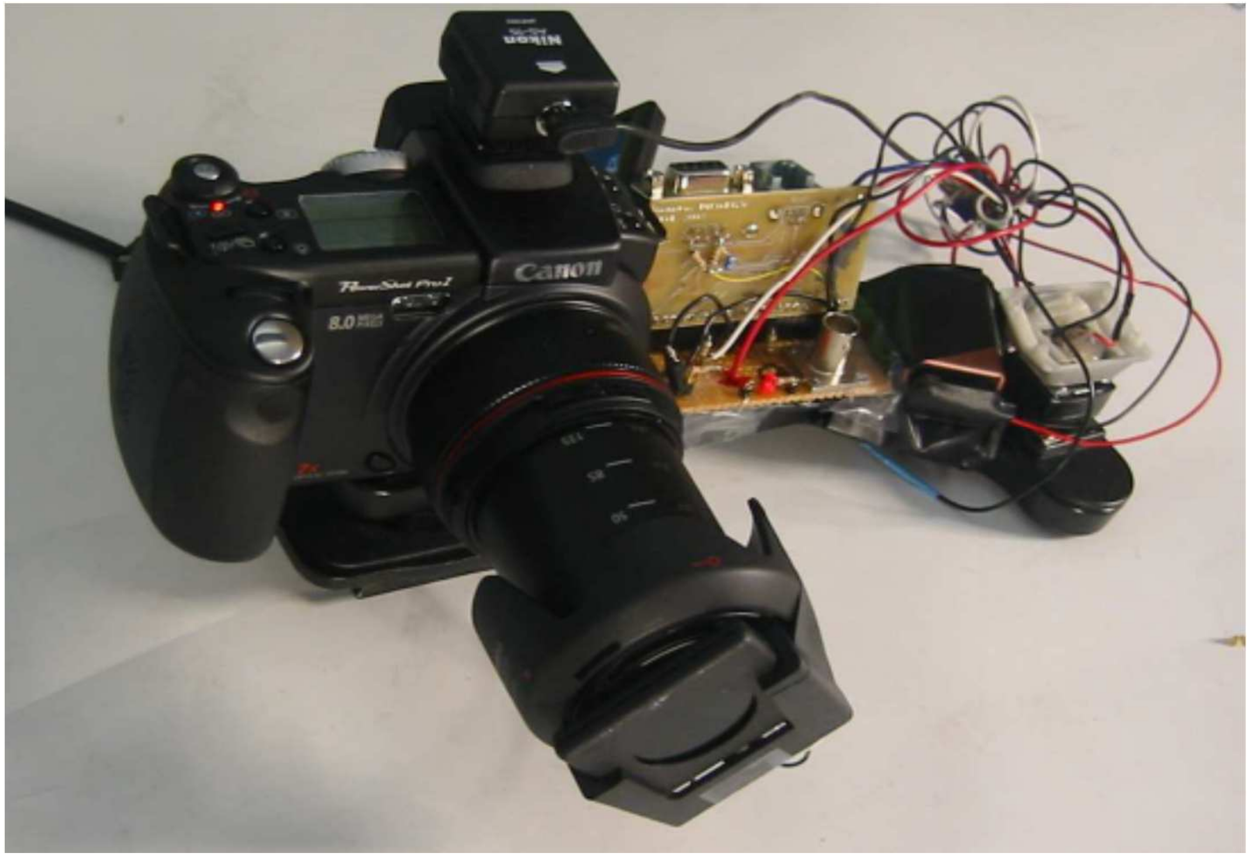
Flutter Shutter: Shutter is OPEN and CLOSED


Traditional
Deblurred Image
Coded Exposure
Deblurred Image
Image of Static Object


485-PCK

Coded Exposure (Flutter Shutter) Camera

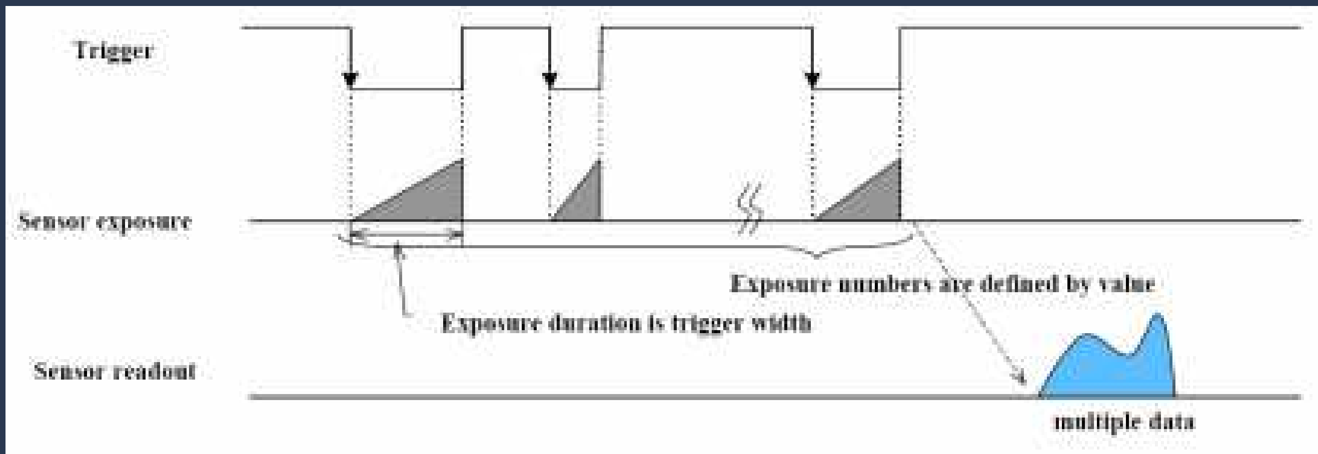
Raskar, Agrawal, Tumblin [Siggraph2006]



Coding in Time: Shutter is opened and closed

Flutter Shutter Video Camera

- Pointgrey Dragonfly2 Camera
- Use Trigger Mode 5
- On-chip, Additional Cost = $0



How to handle focus blur?

Coded <u>Exposure</u> (Flutter Shutter)

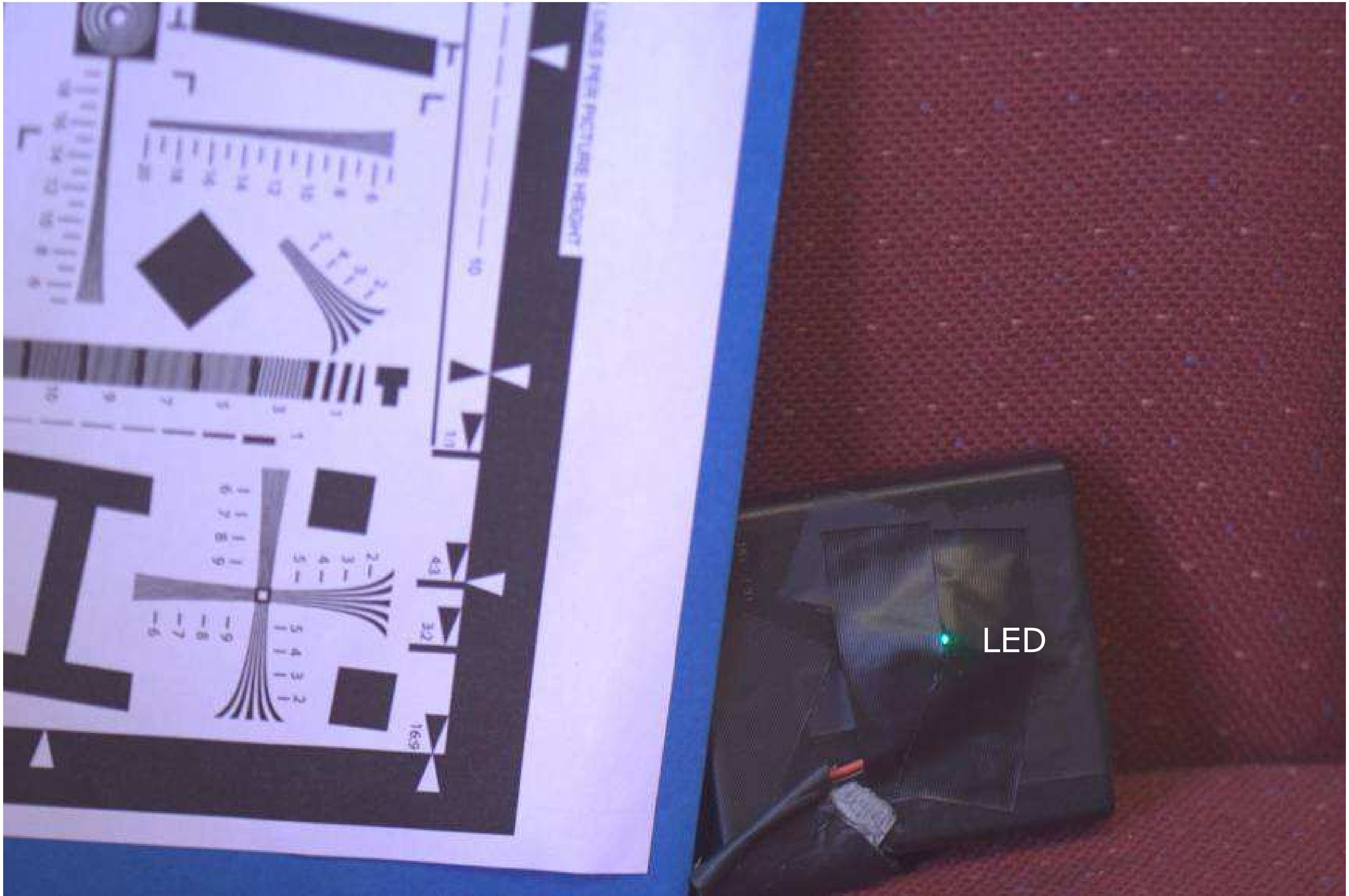
Raskar, Agrawal, Tumblin
SIGGRAPH 2006

Temporal 1-D broadband code:
Motion Deblurring

Coded <u>Aperture</u>

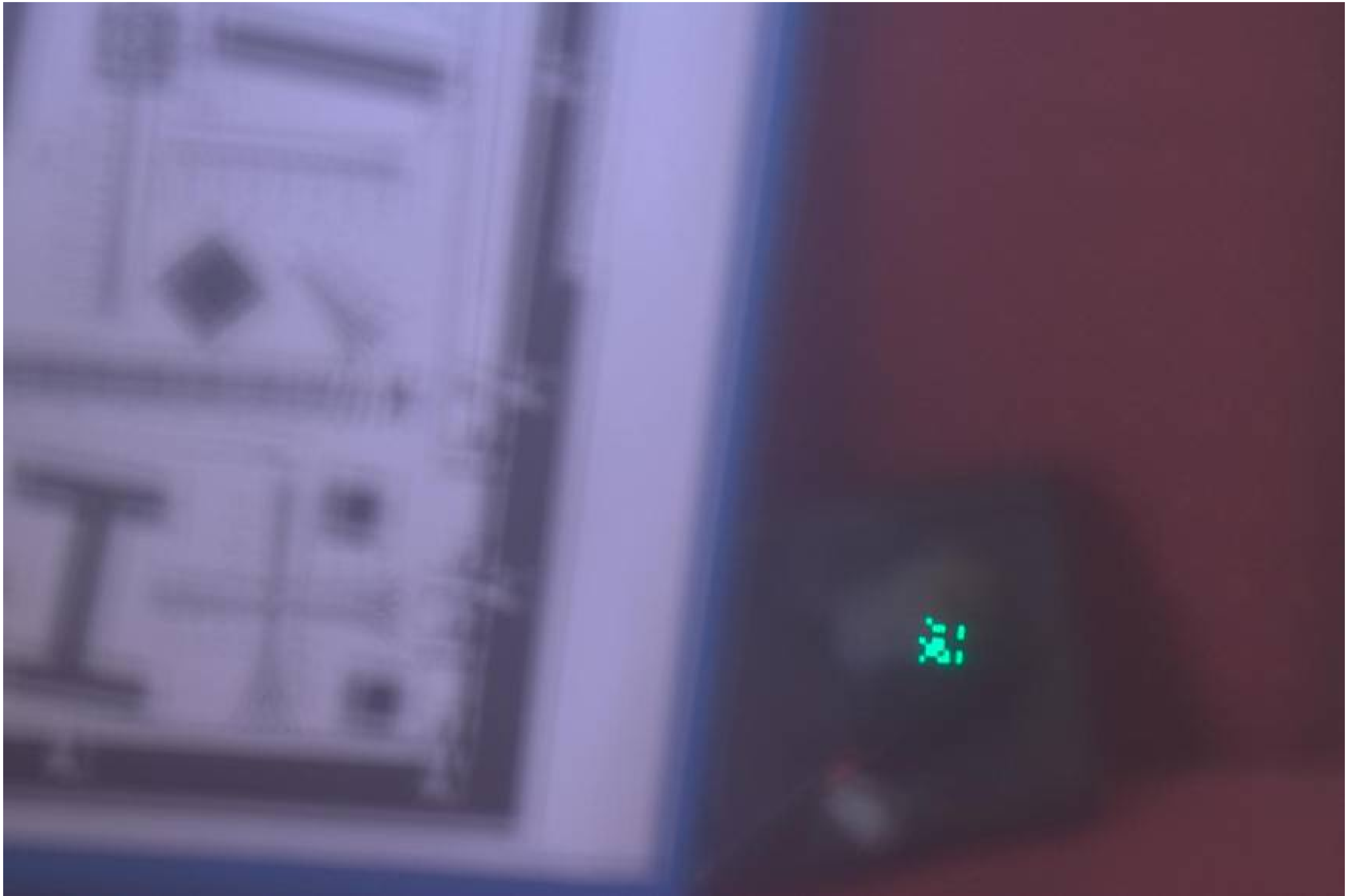
with Veeraraghavan, Raskar, Tumblin, & Mohan,
SIGGRAPH 2007

Spatial 2-D broadband code:
Focus Deblurring



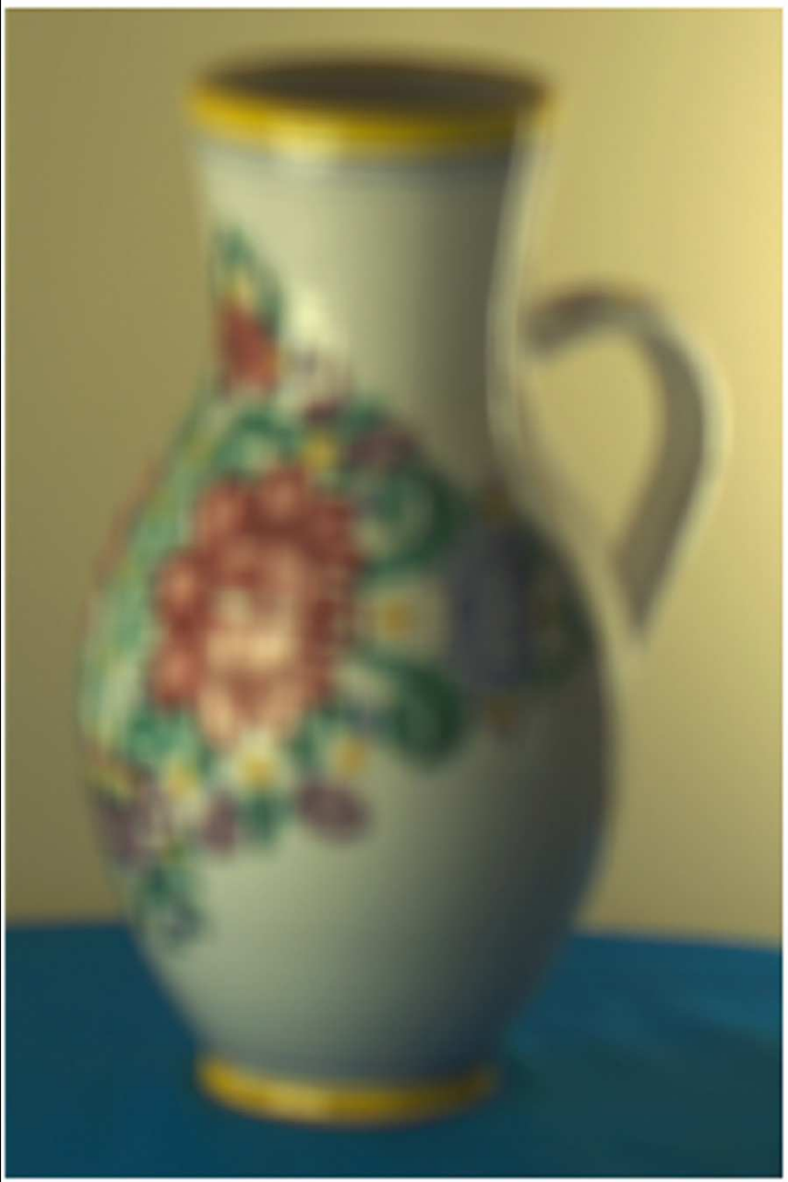
In Focus Photo

Out of Focus Photo: Open Aperture



Out of Focus Photo: Coded Aperture

Blurred Photos



Open Aperture

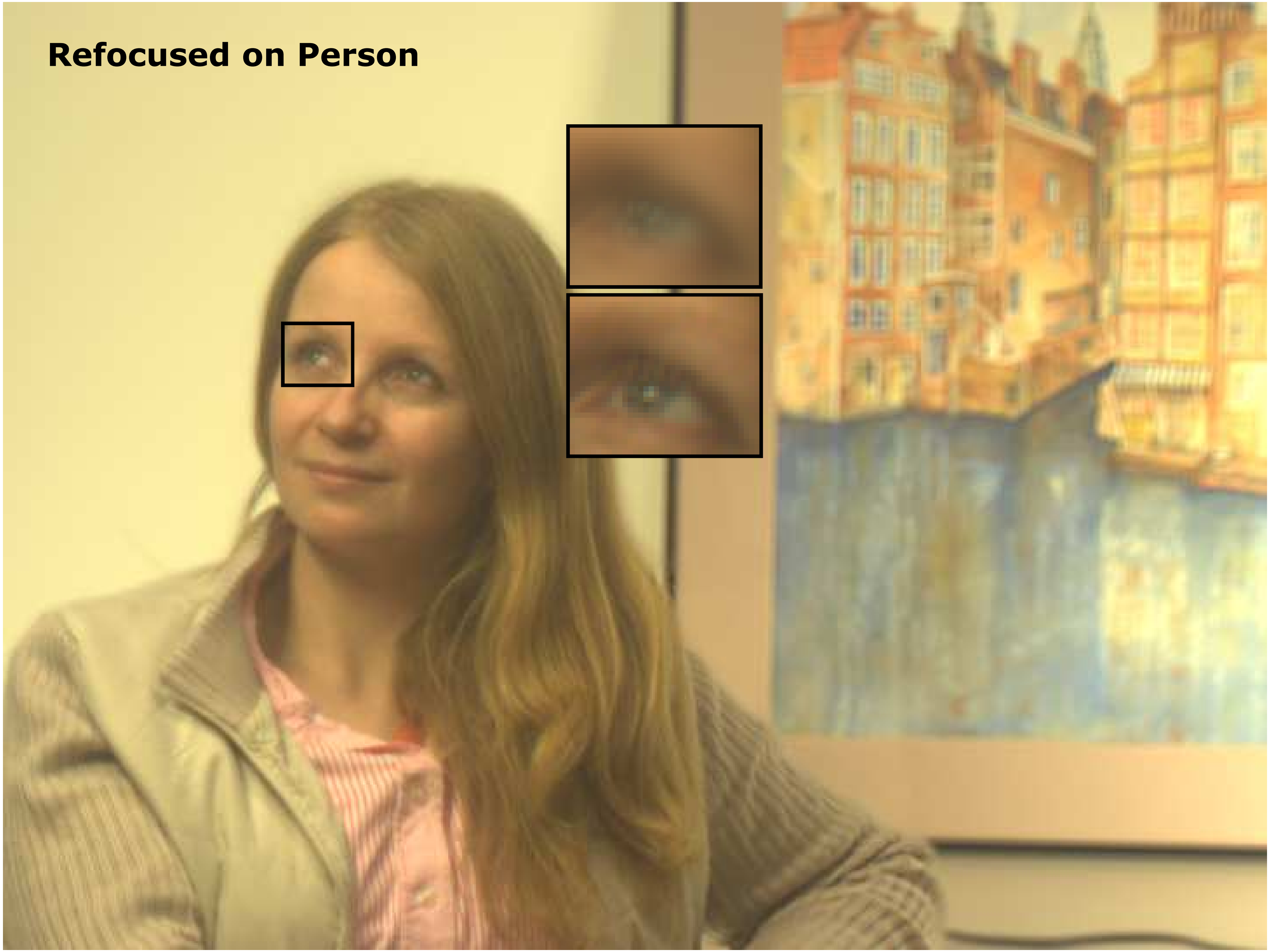
Coded Aperture, 7 * 7 Mask

Deblurred Photos

Open Aperture

Coded Aperture, 7 * 7 Mask

Captured Blurred Photo


Refocused on Person


Beal.

Coded Imaging

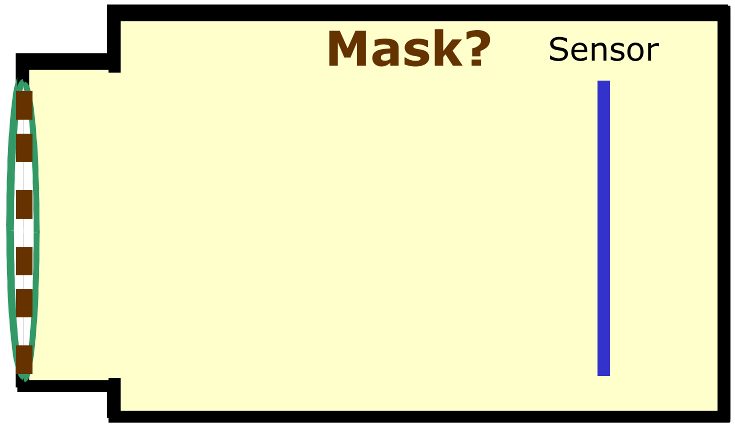
Blocking Light == More Information

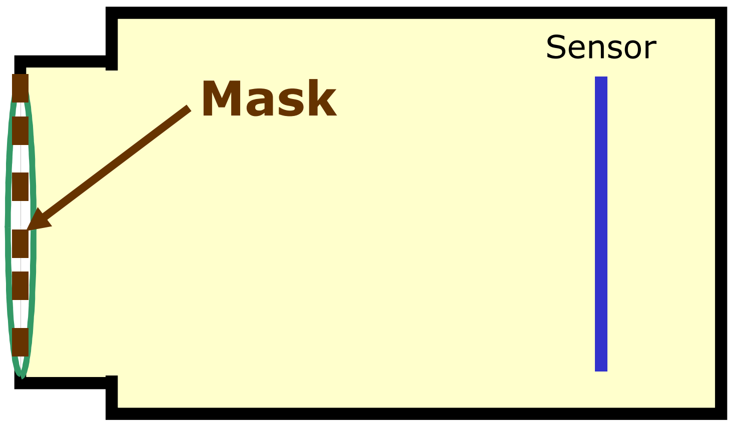
Coded Exposure
Coding in Time

Coded Aperture
Coding in Space

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
?	Space and Angle
?	Space, Time, Angle
?	Space and Time





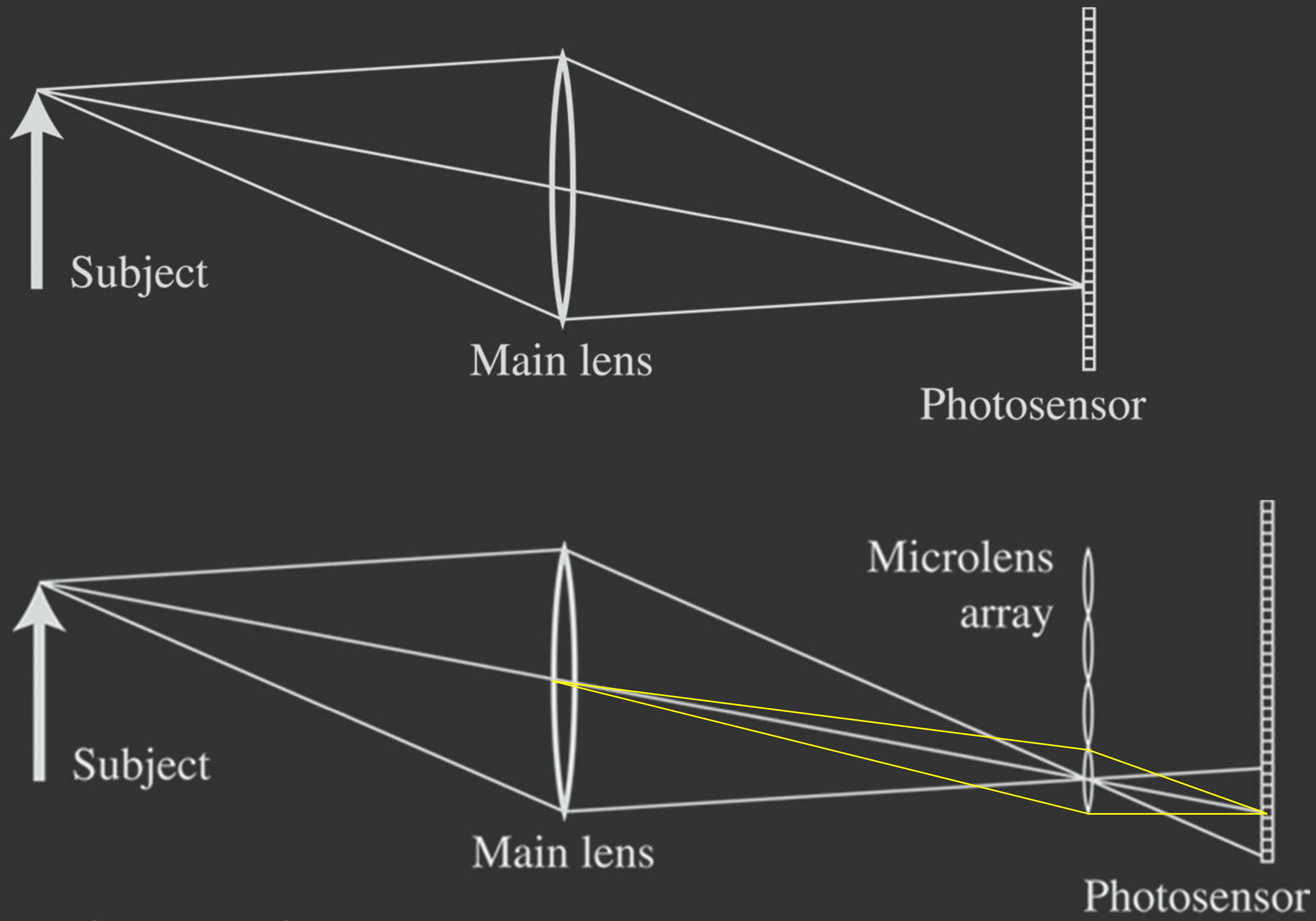
Full Resolution Digital Refocusing:

Coded Aperture Camera

4D Light Field from 2D Photo:

Heterodyne Light Field Camera

Lytro: Lenslet-based Light Field camera

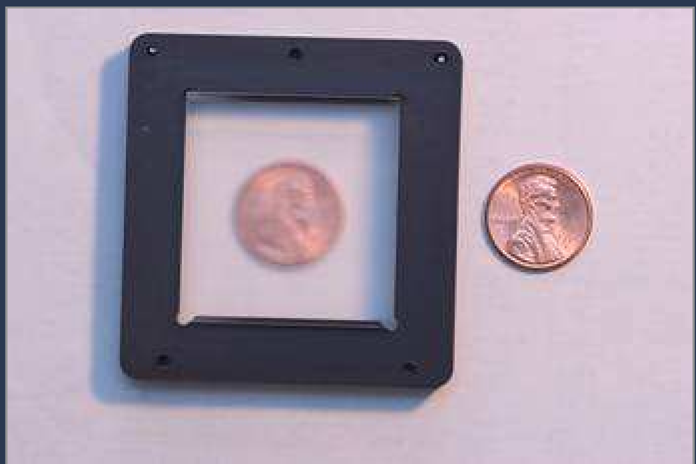


Adelson and Wang, 1992, Ng et al. 2005

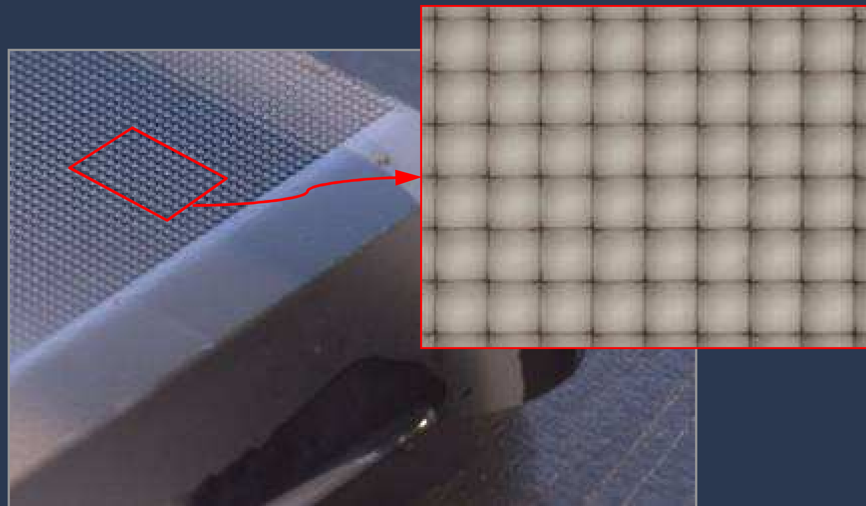
Stanford Plenoptic Camera (Lytro) [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



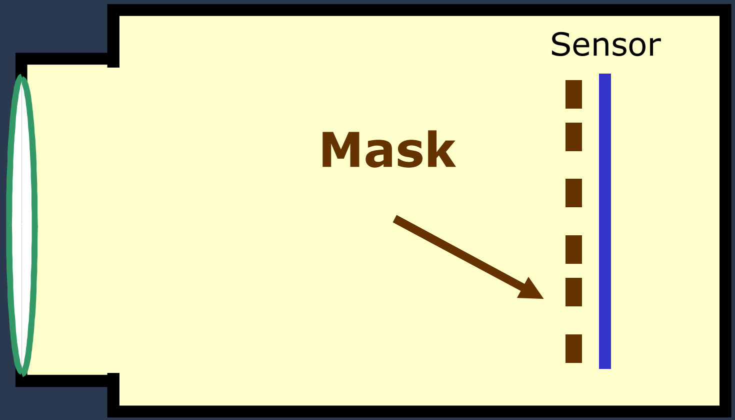
Adaptive Optics microlens array



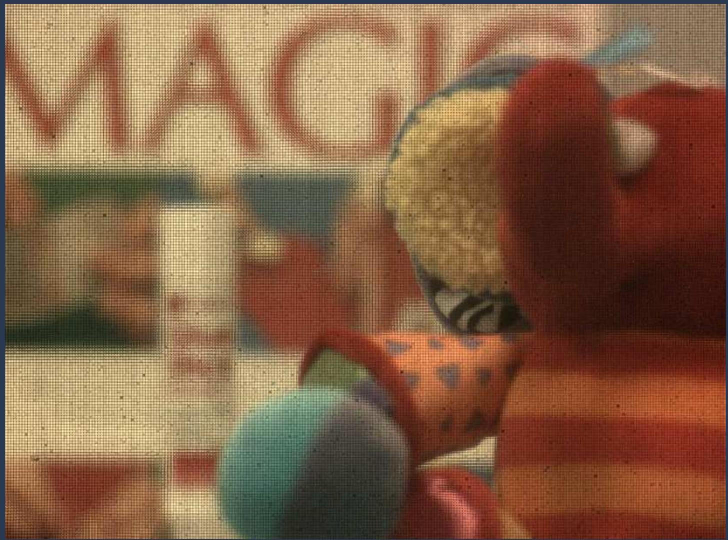
125μ square-sided microlenses

4000 4000 pixels 292 292 lenses = 14 14 pixels per lens

Mask based Light Field Camera (SIGGRAPH 2007)



- Sum of Cosines Mask
- Pinhole Array Mask
- Tiled Broadband Mask

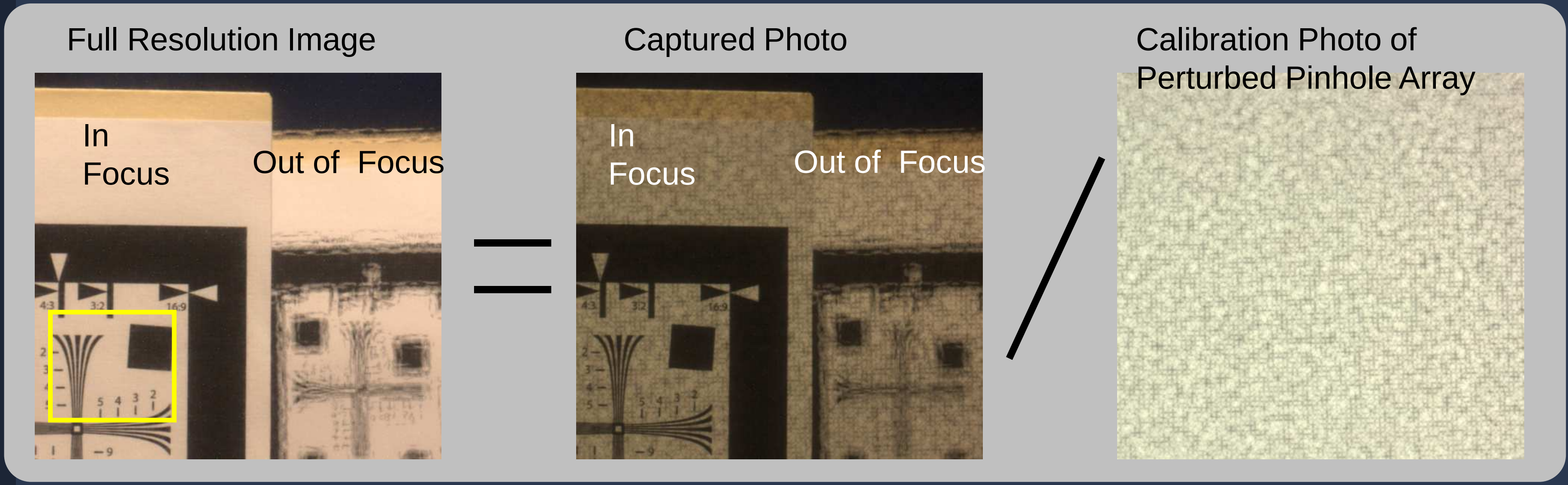


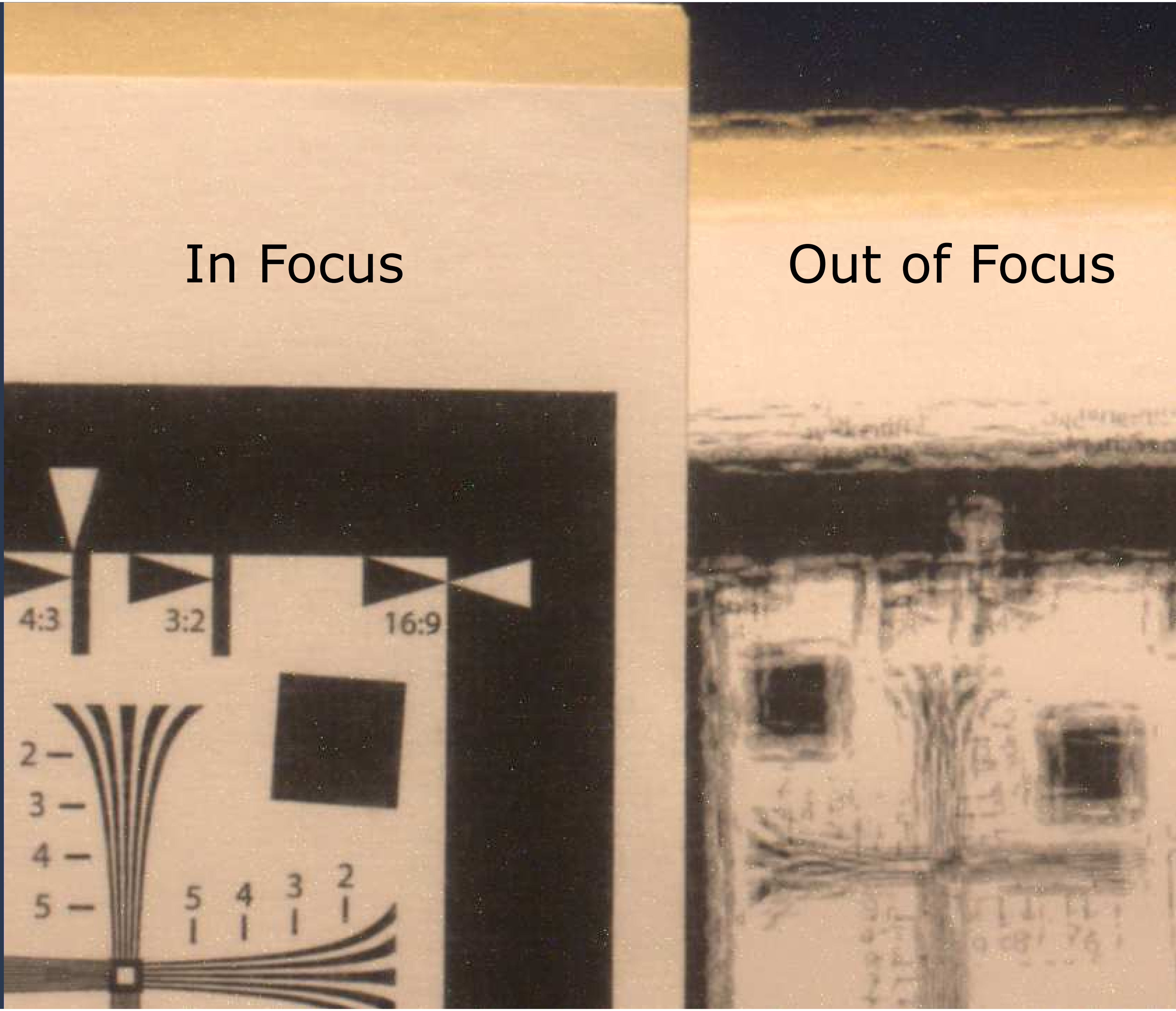
Captured Light Field

Digital Refocusing

Recovering Full Resolution 2D Image

- For in-focus scene
- Inserting Mask == Spatially Varying Image Attenuation
- Compensate using calibration image

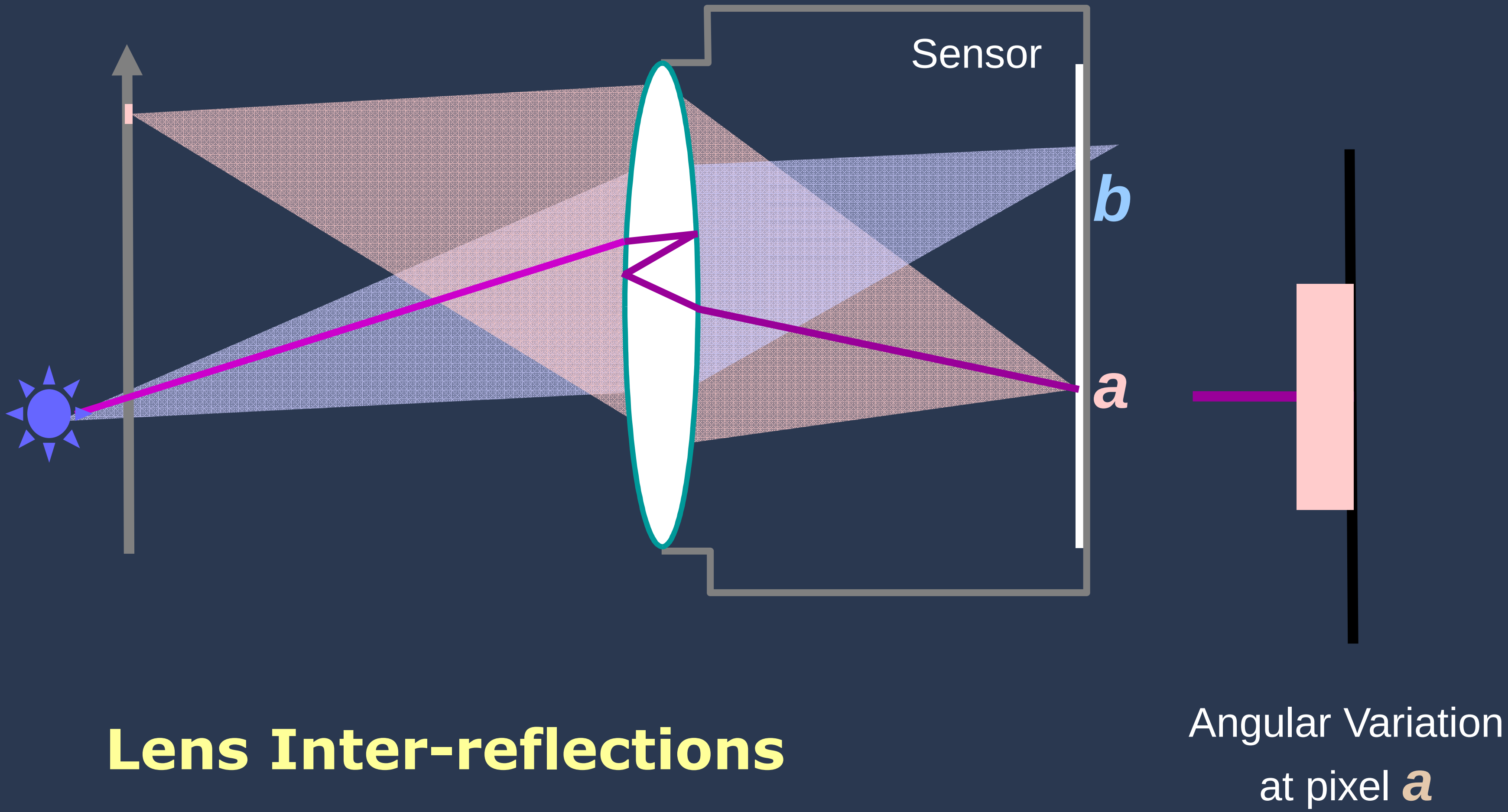



In Focus
Out of Focus
4:3
3:2
16:9
2
3
4
5
5
4
3
2

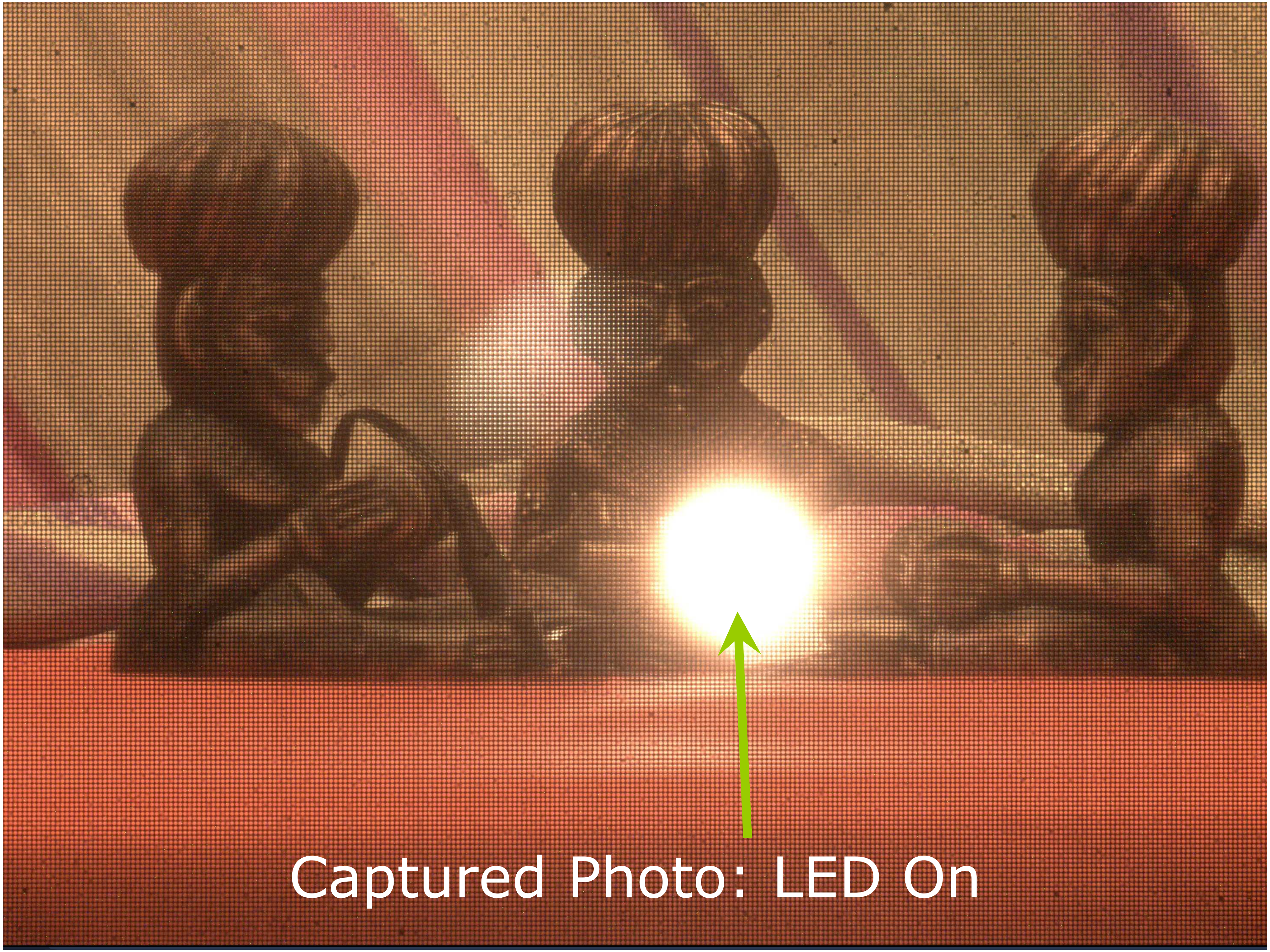
Lens Glare Reduction using Light Field

Effects of Glare on Image

- Hard to model, Low Frequency in 2D
- But reflection glare is outlier in 4D ray-space



Lens Inter-reflections

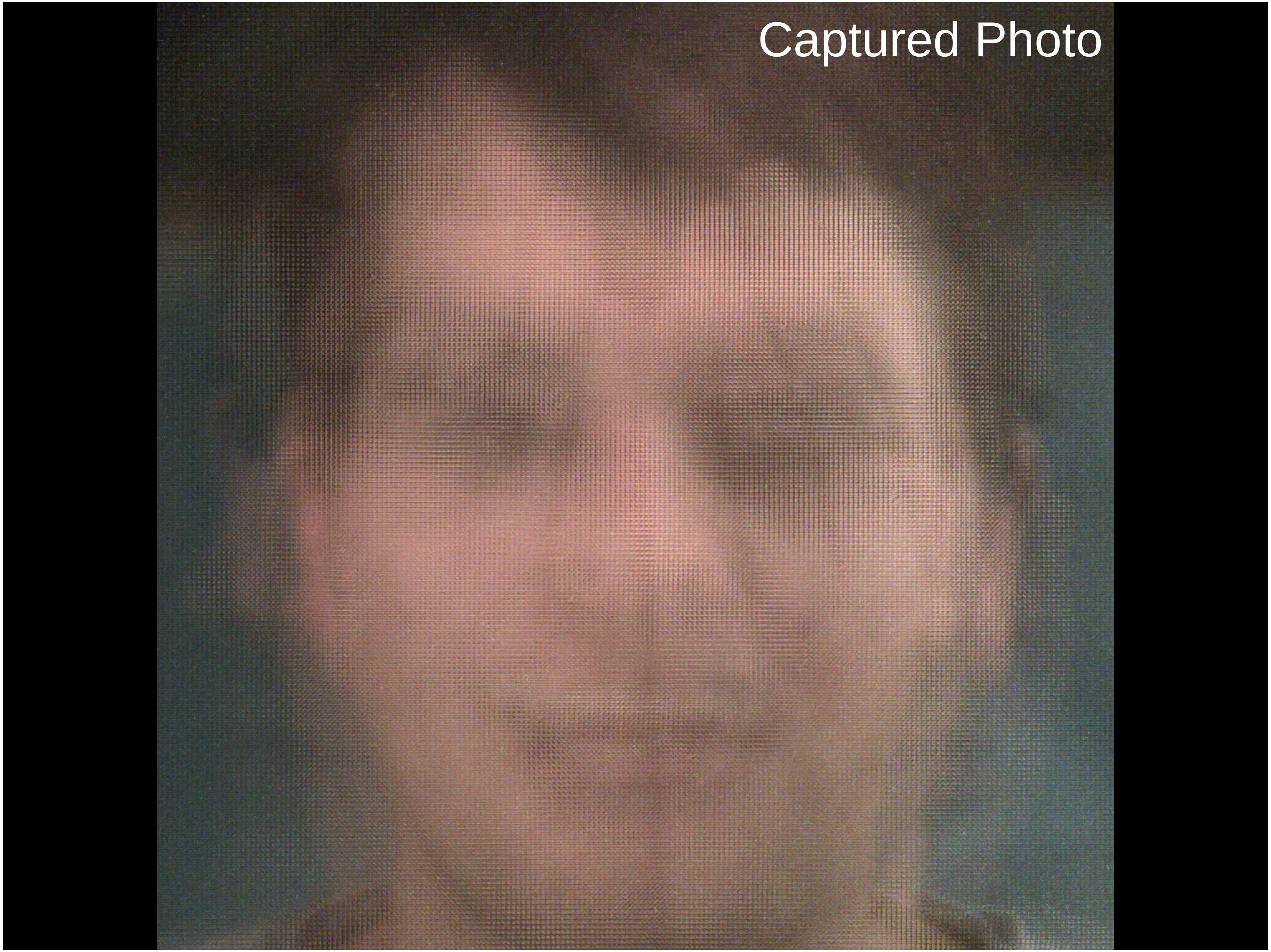

Captured Photo: LED On


v
u
y
x

Sequence of Sub-Aperture Views

Traditional Camera Photo

Glare Reduced Photo


Captured Photo

Video from Single-Shot (Temporal Frames)

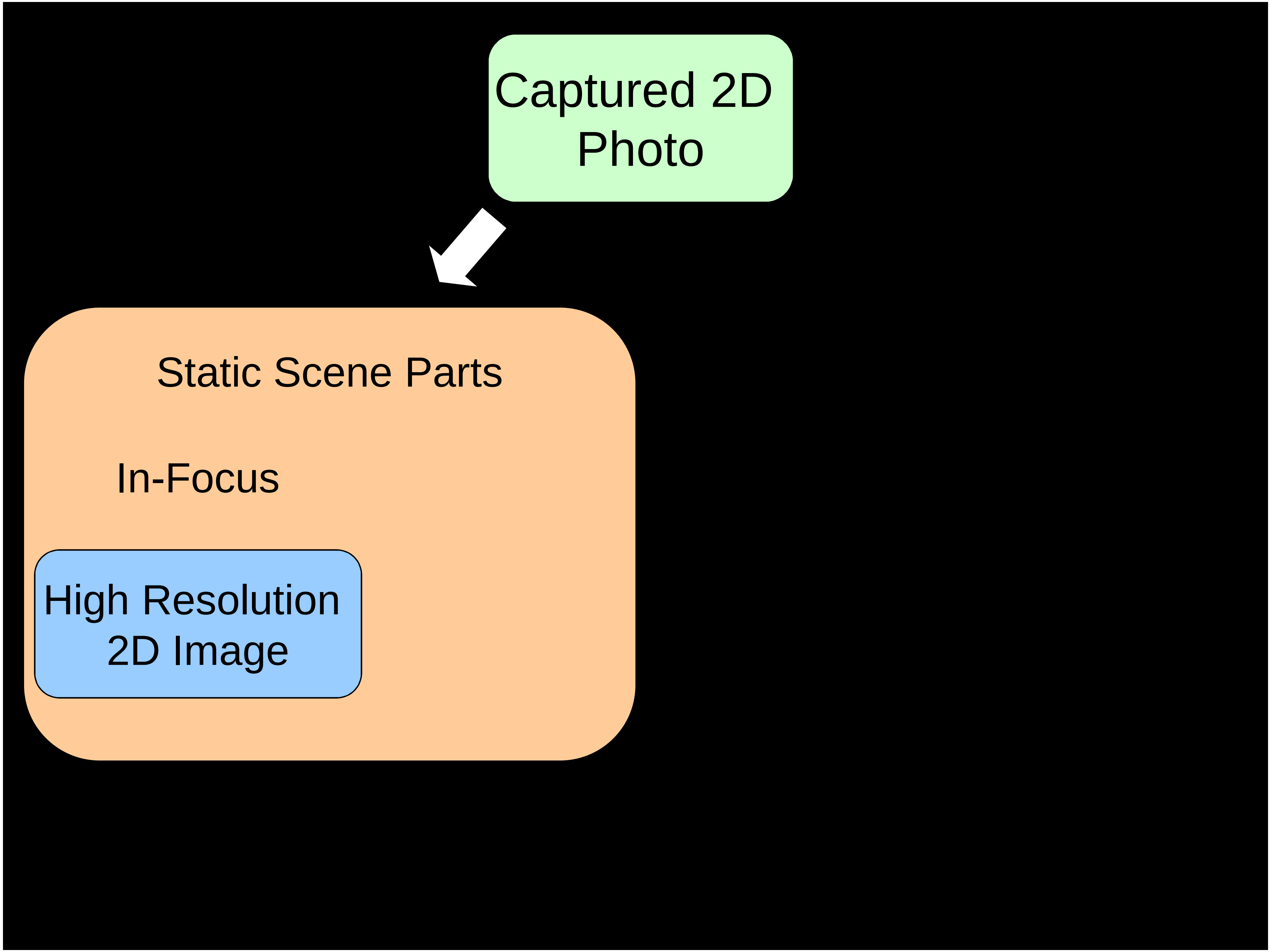

Captured Photo

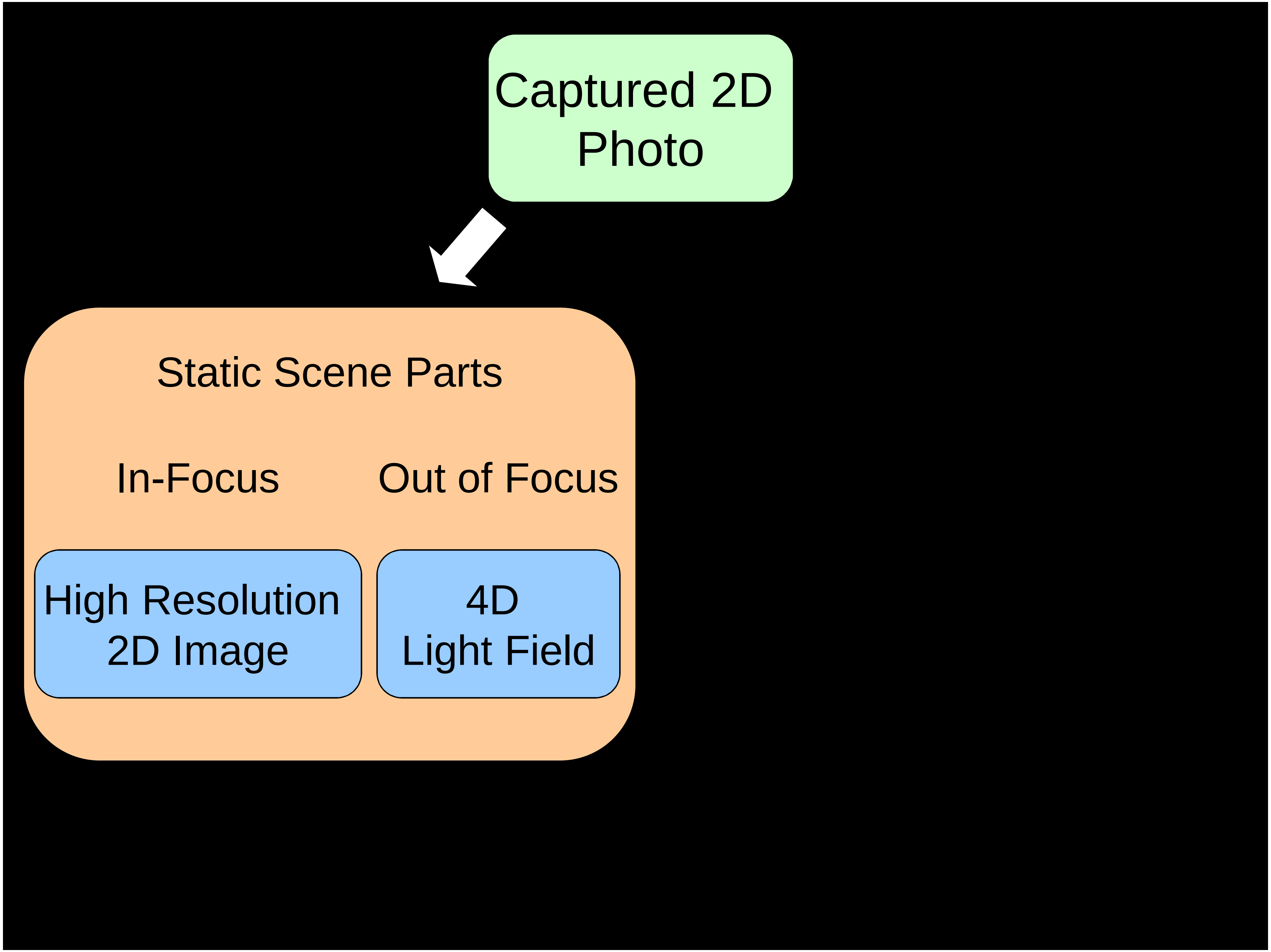

Rotating Doll in Focus

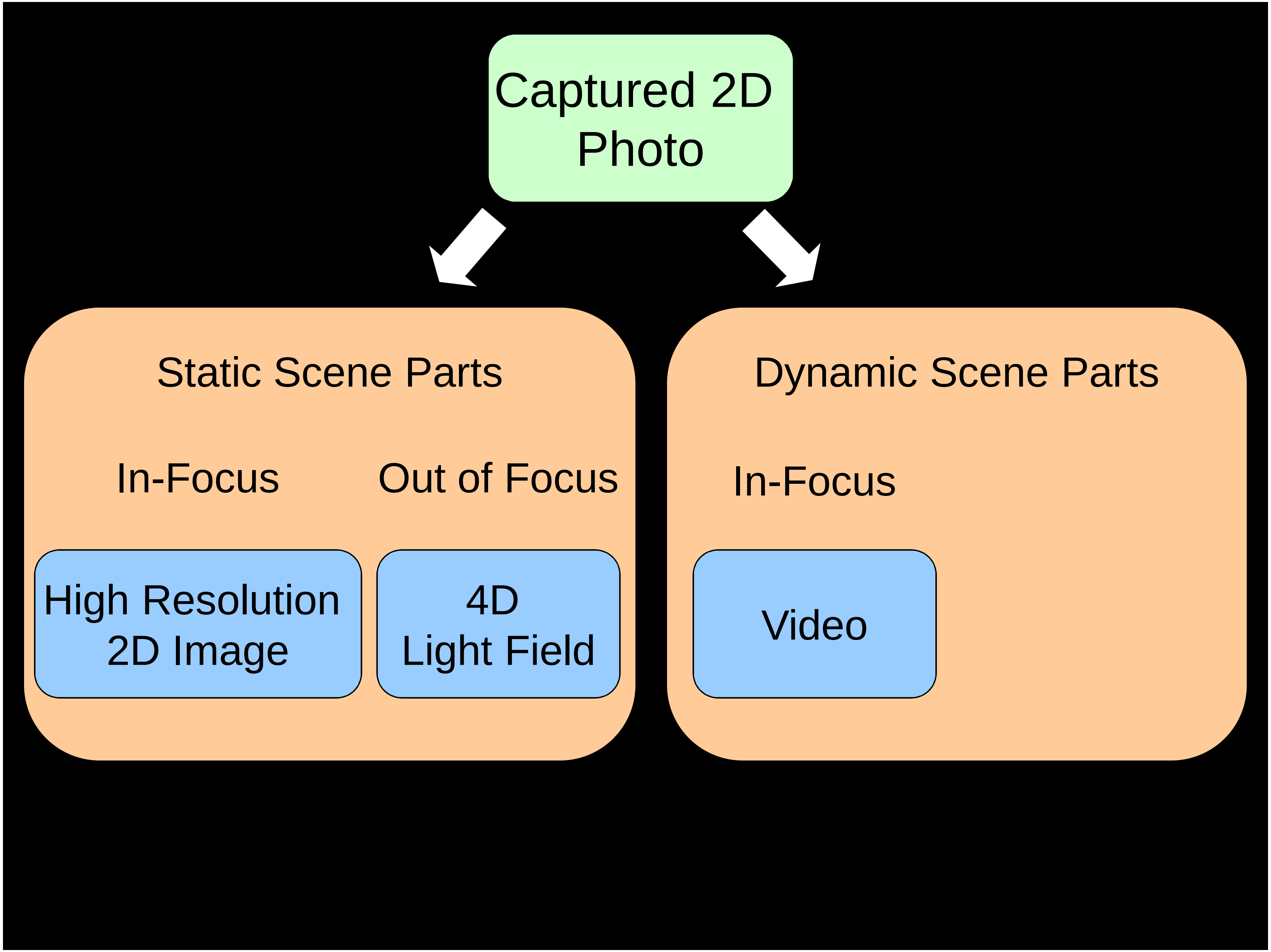
Reinterpretable Camera

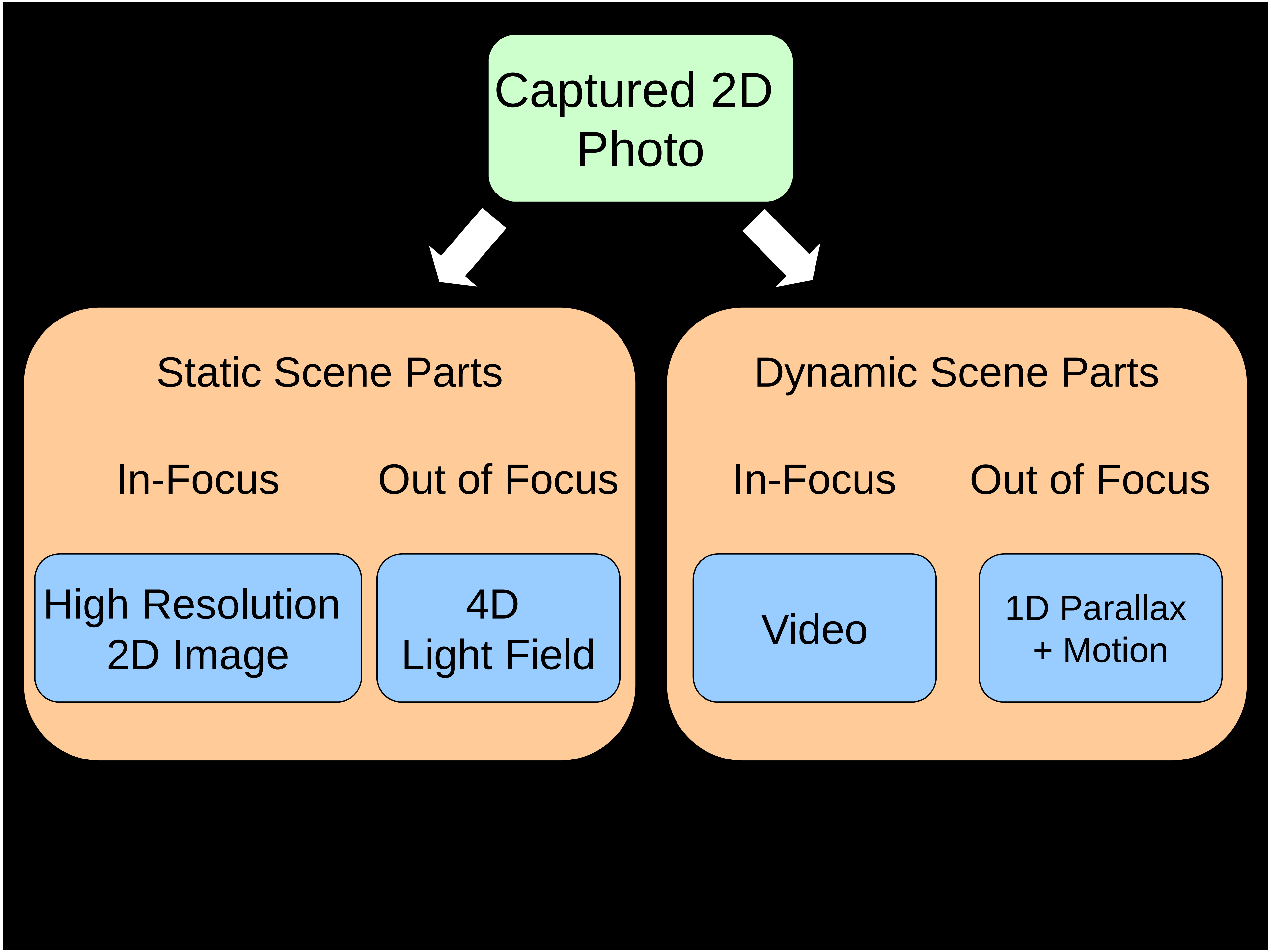
- Resolution tradeoff for Conventional Imaging
  - Fixed before capture
    - video camera, lightfield camera
  - Scene independent
- Resolution tradeoff for Reinterpretable Camera
  - Variable in post-capture
  - Scene dependent
  - Different for different parts of the scene/captured photo

Captured 2D Photo


Captured 2D Photo
Static Scene Parts
In-Focus
High Resolution 2D Image

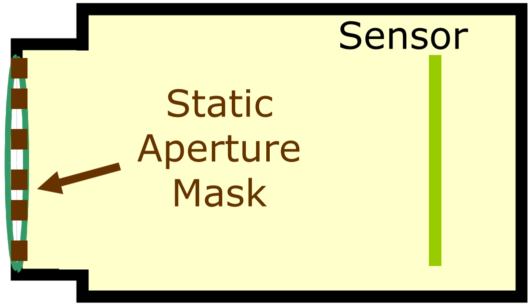

Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field


Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field
Dynamic Scene Parts
In-Focus
Video



Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field
Dynamic Scene Parts
In-Focus
Out of Focus
Video
1D Parallax + Motion

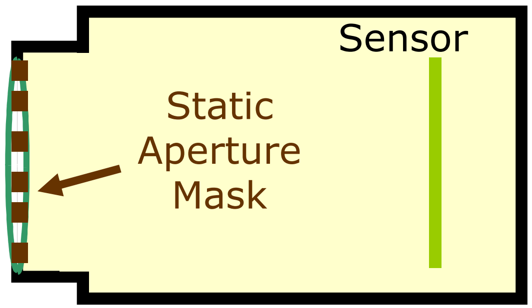
Coded Aperture



SIGGRAPH 2007

Digital
Refocusing

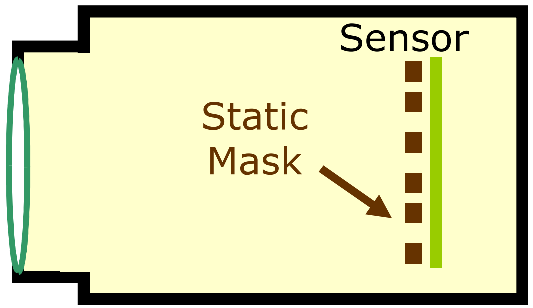
Coded Aperture



SIGGRAPH 2007

Digital
Refocusing

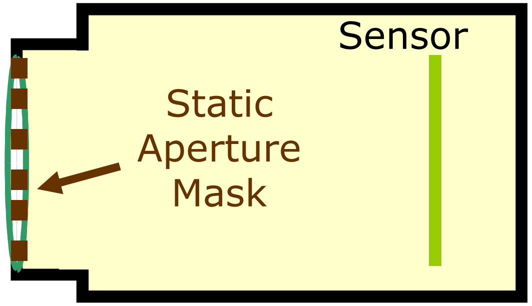
Optical Heterodyning



SIGGRAPH 2007

Light Field
Capture

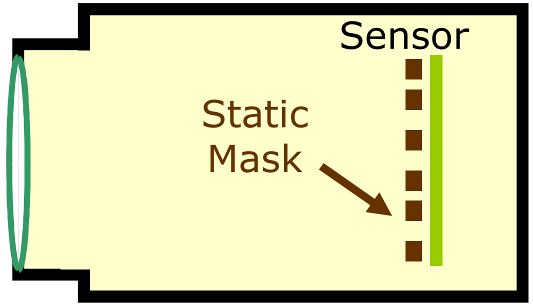
Coded Aperture



SIGGRAPH 2007

Digital
Refocusing

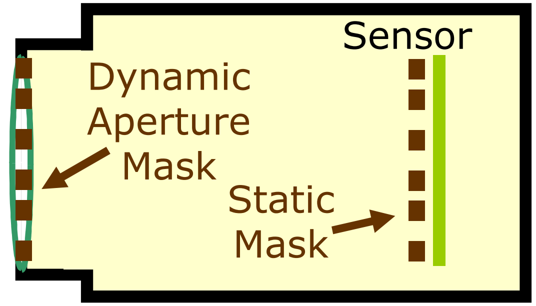
Optical Heterodyning



SIGGRAPH 2007

Light Field
Capture

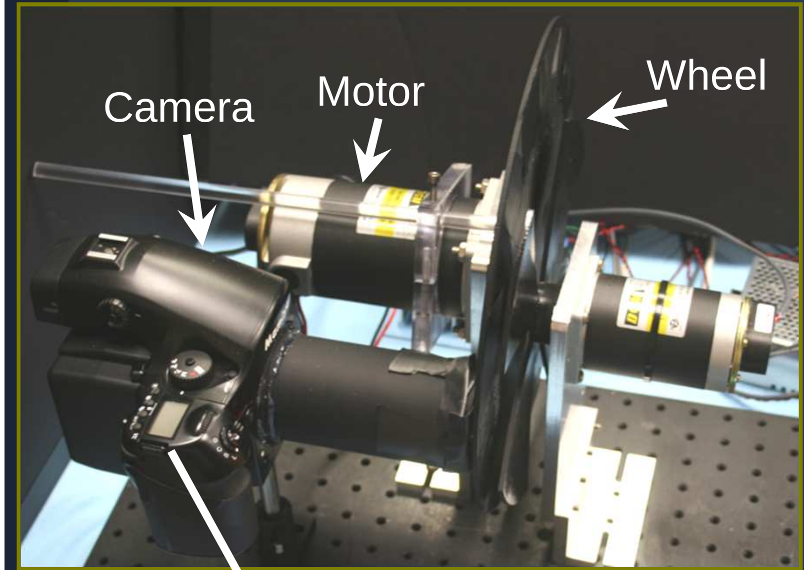
Reinterpretable Camera

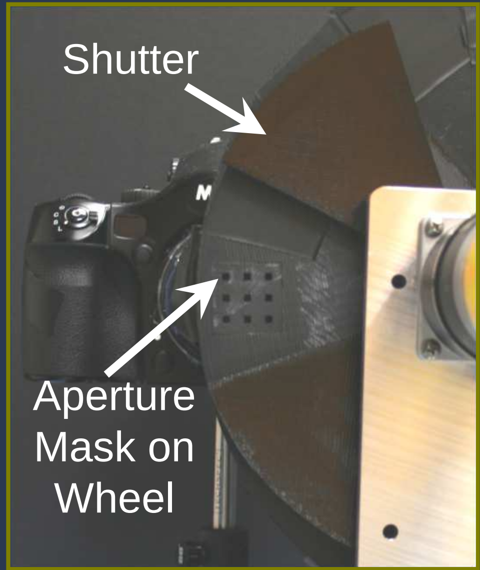


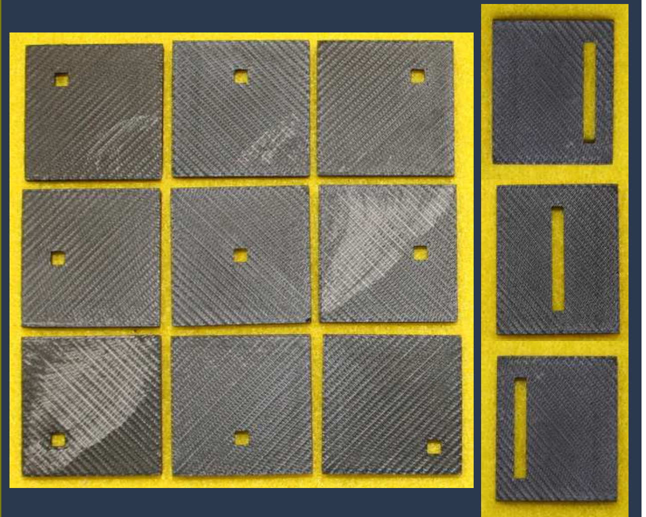
Eurographics 2010

Post-Capture
Resolution Control

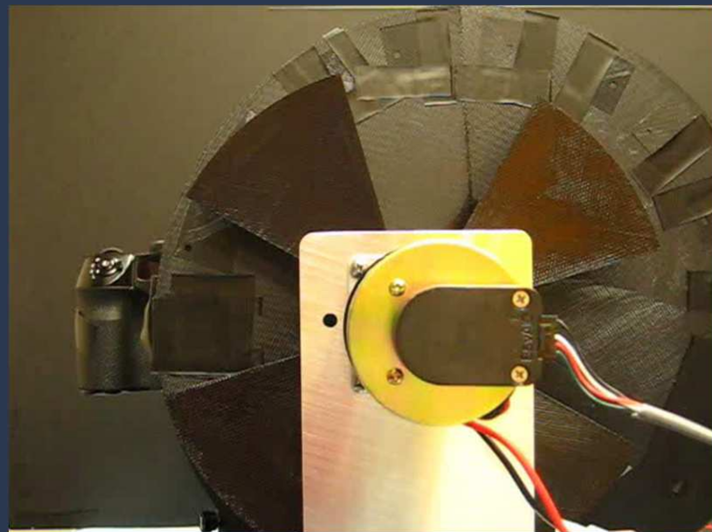
Implementation

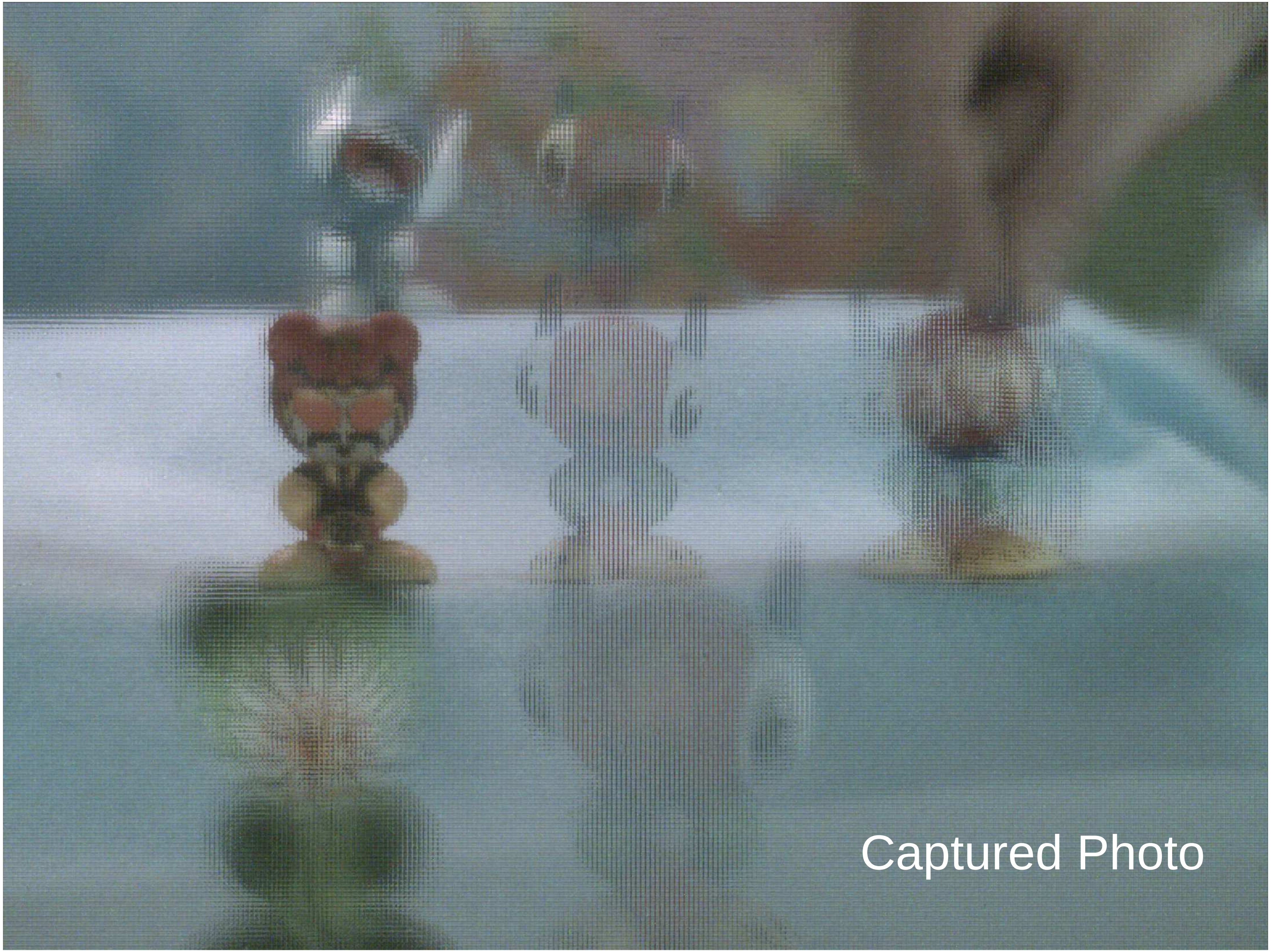


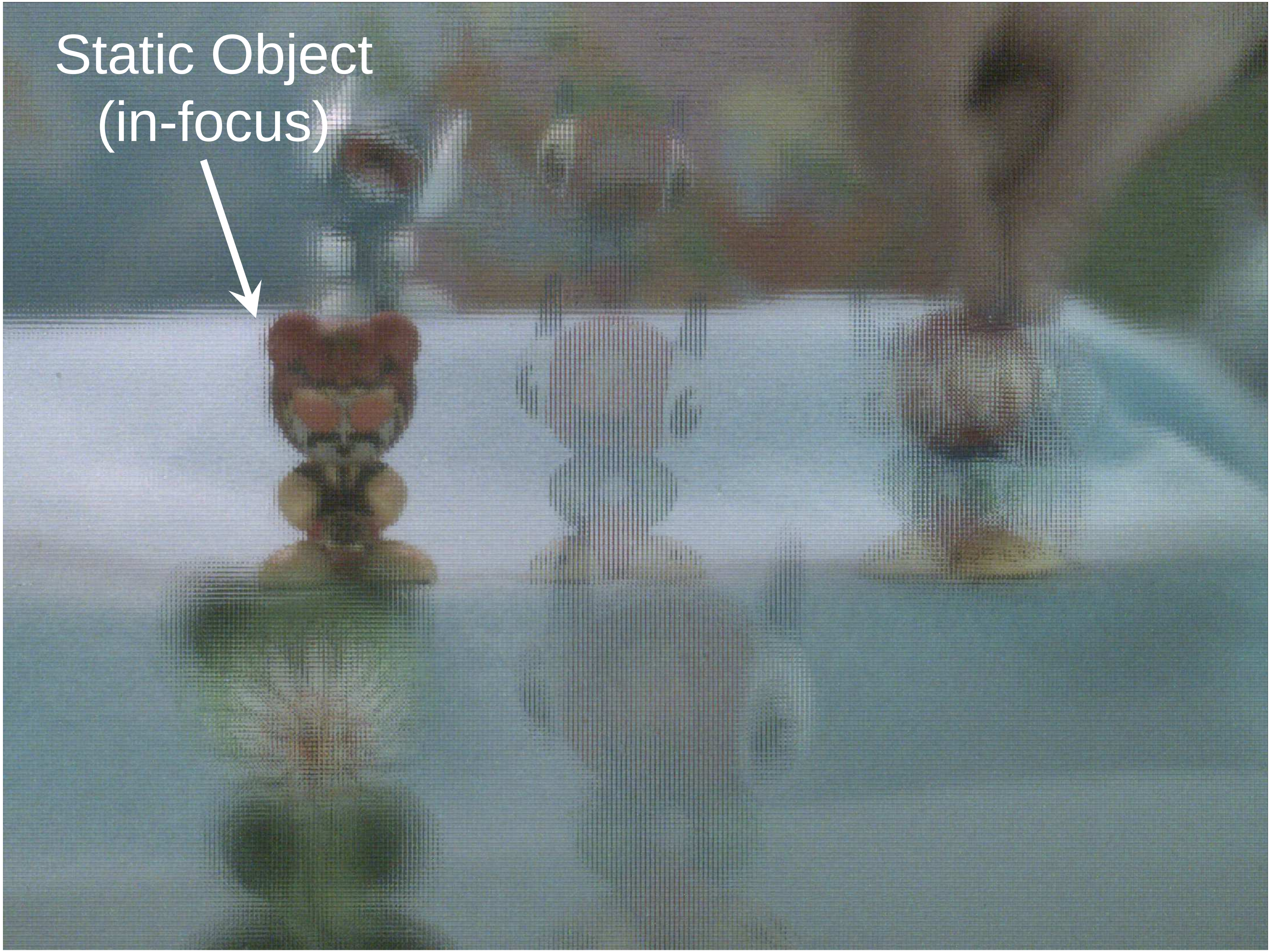


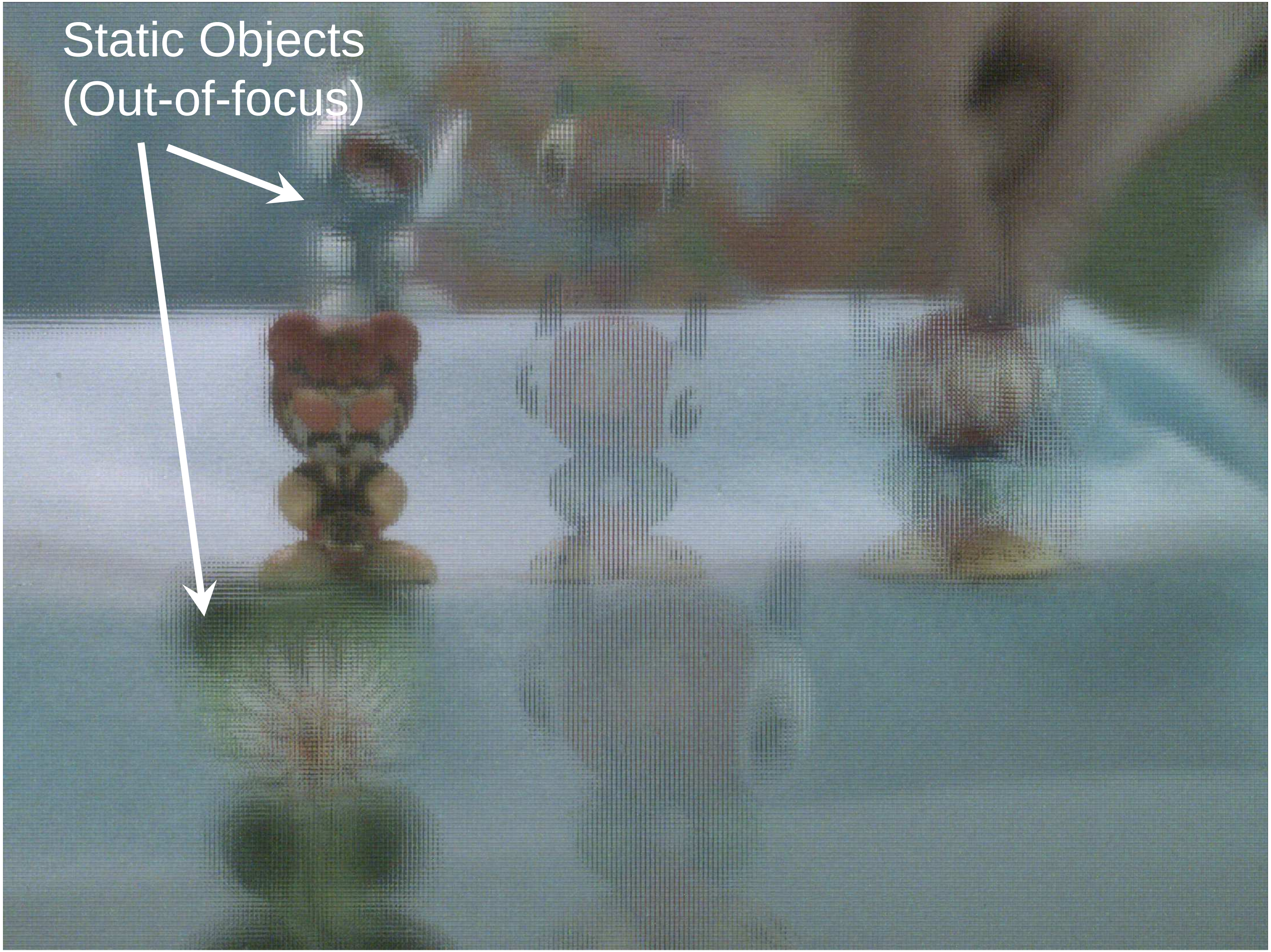


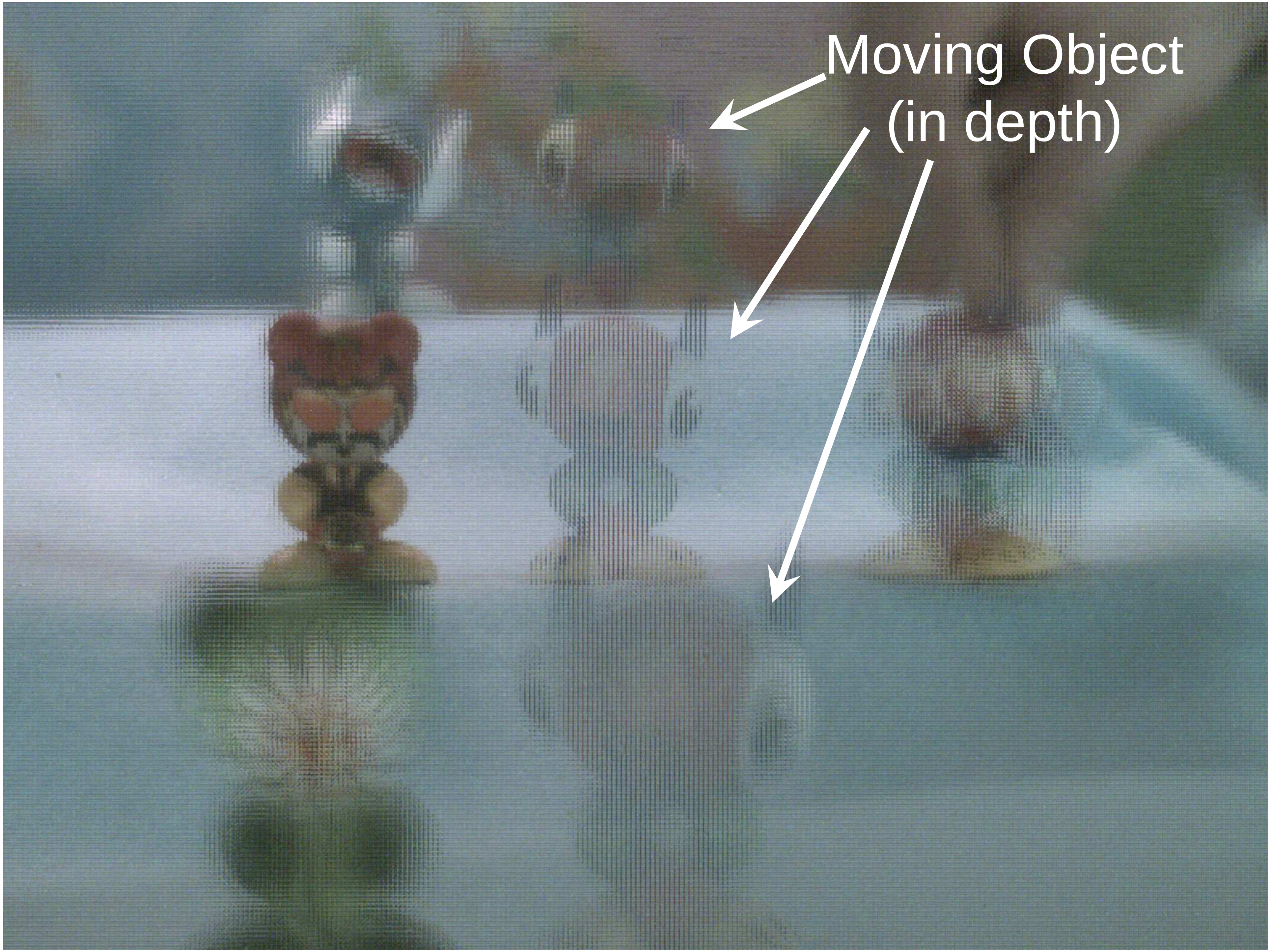
Near-Sensor Mask

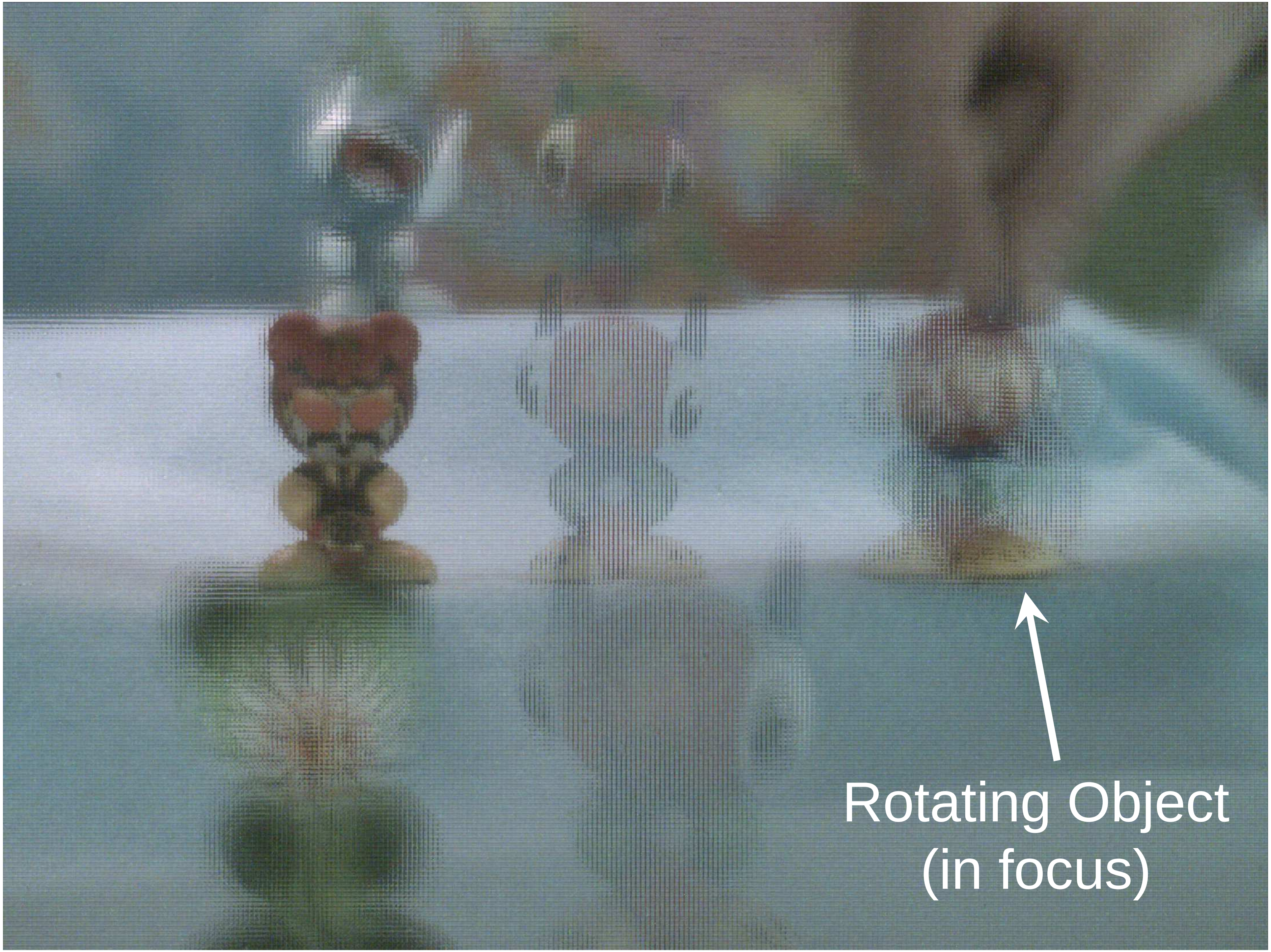


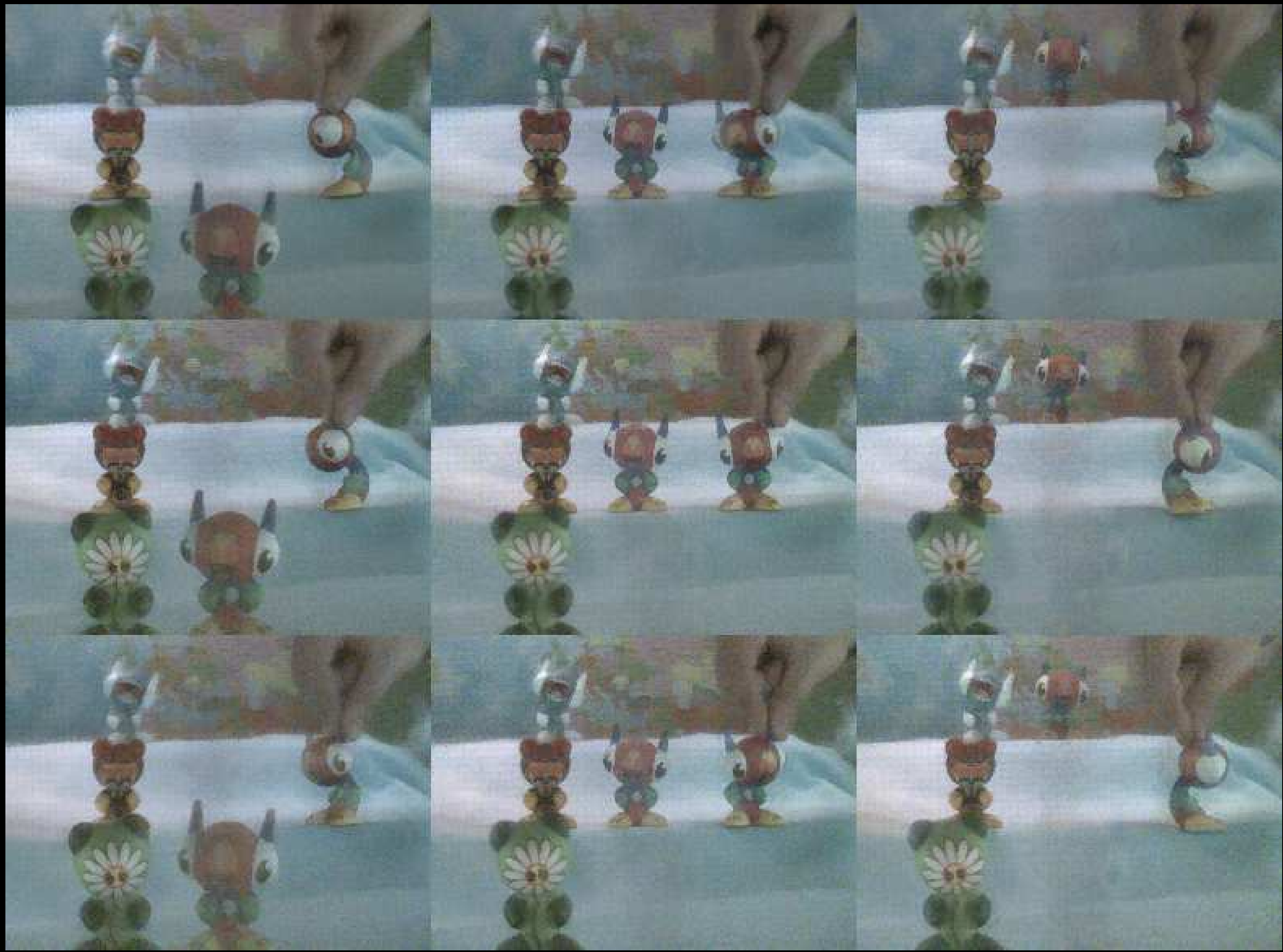

Captured Photo


Static Object
(in-focus)

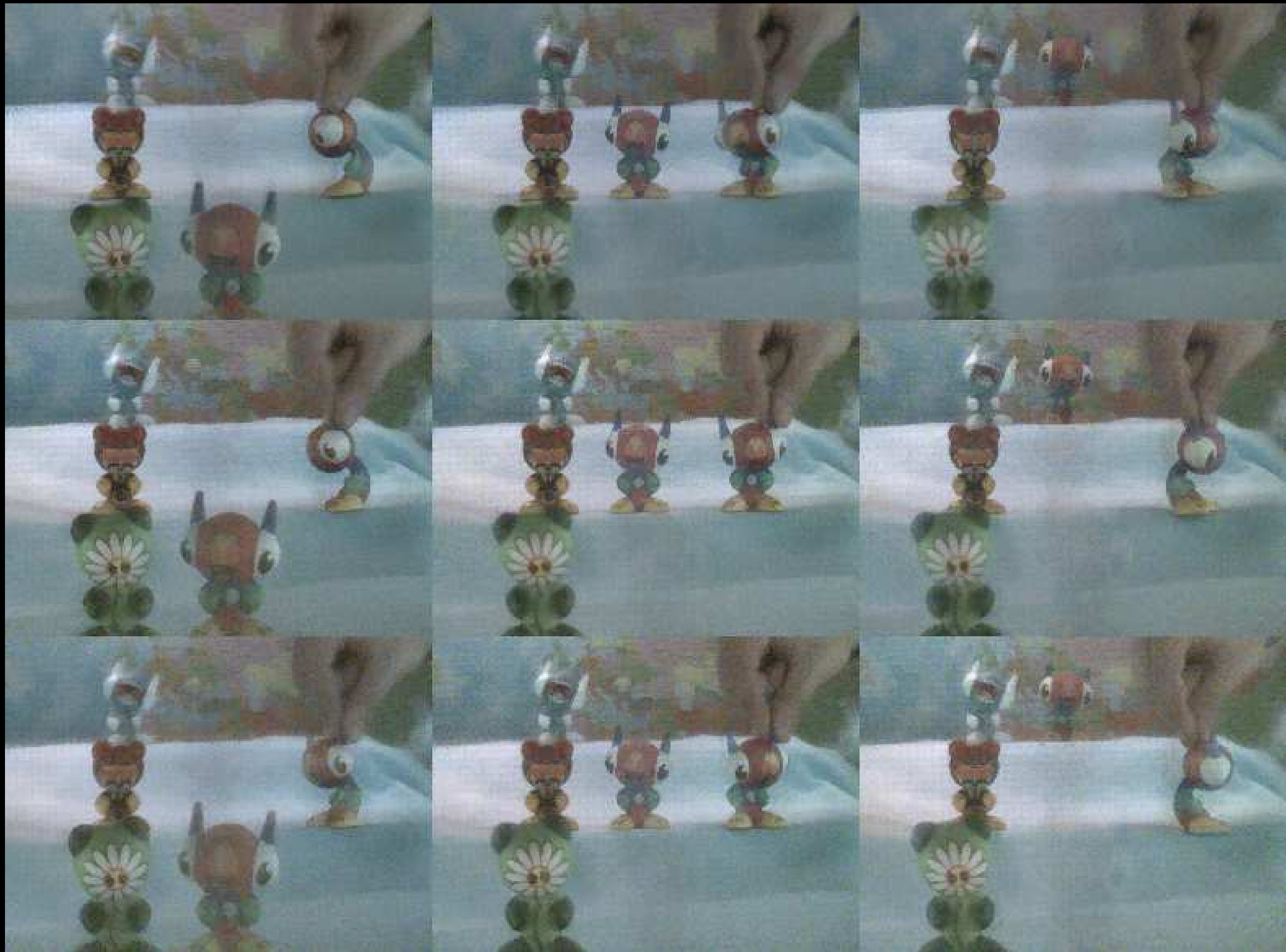

Static Objects
(Out-of-focus)


Moving Object
(in depth)


Rotating Object
(in focus)



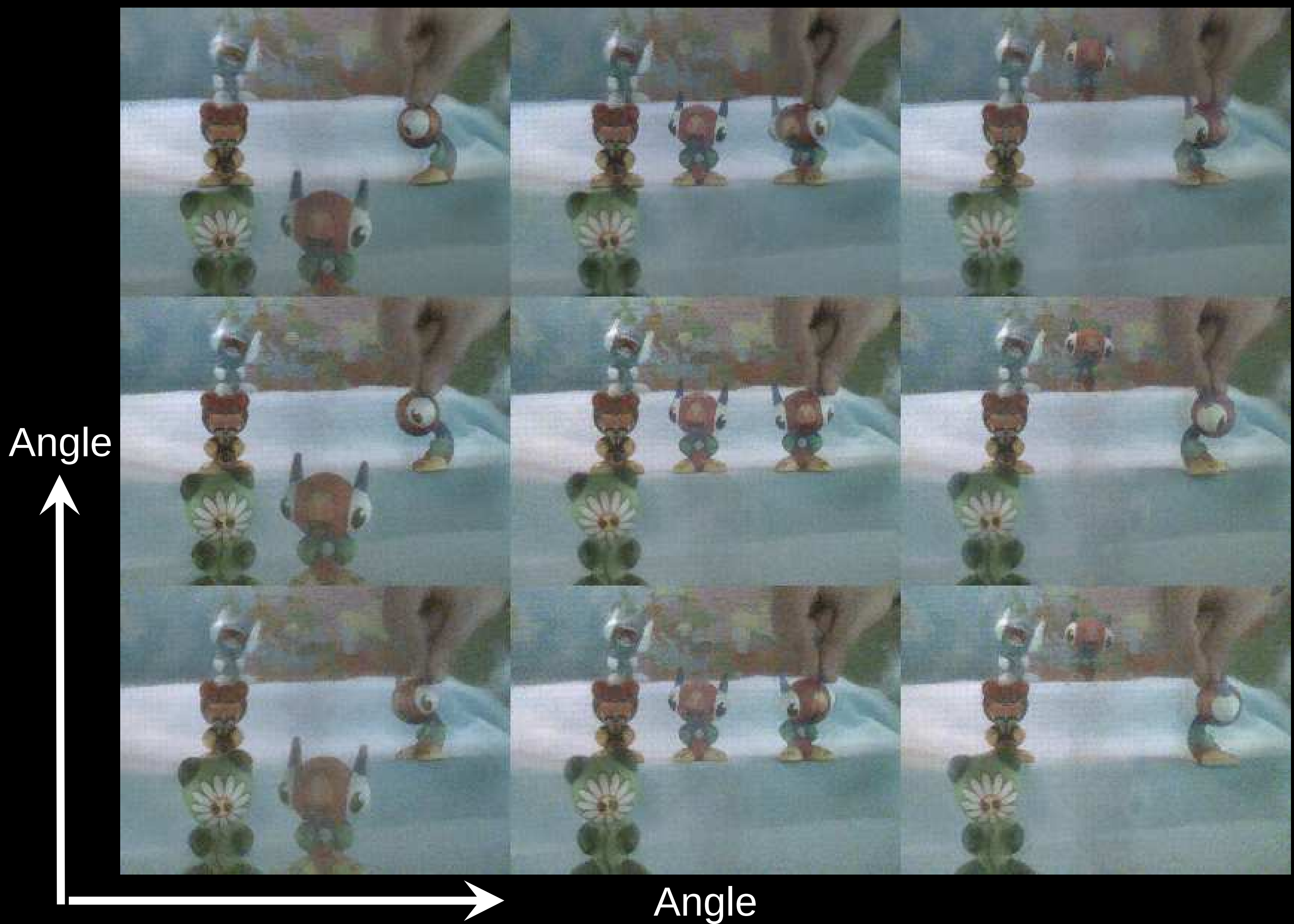
Reconstructed Sub-Aperture Views (3 by 3 Light Field)

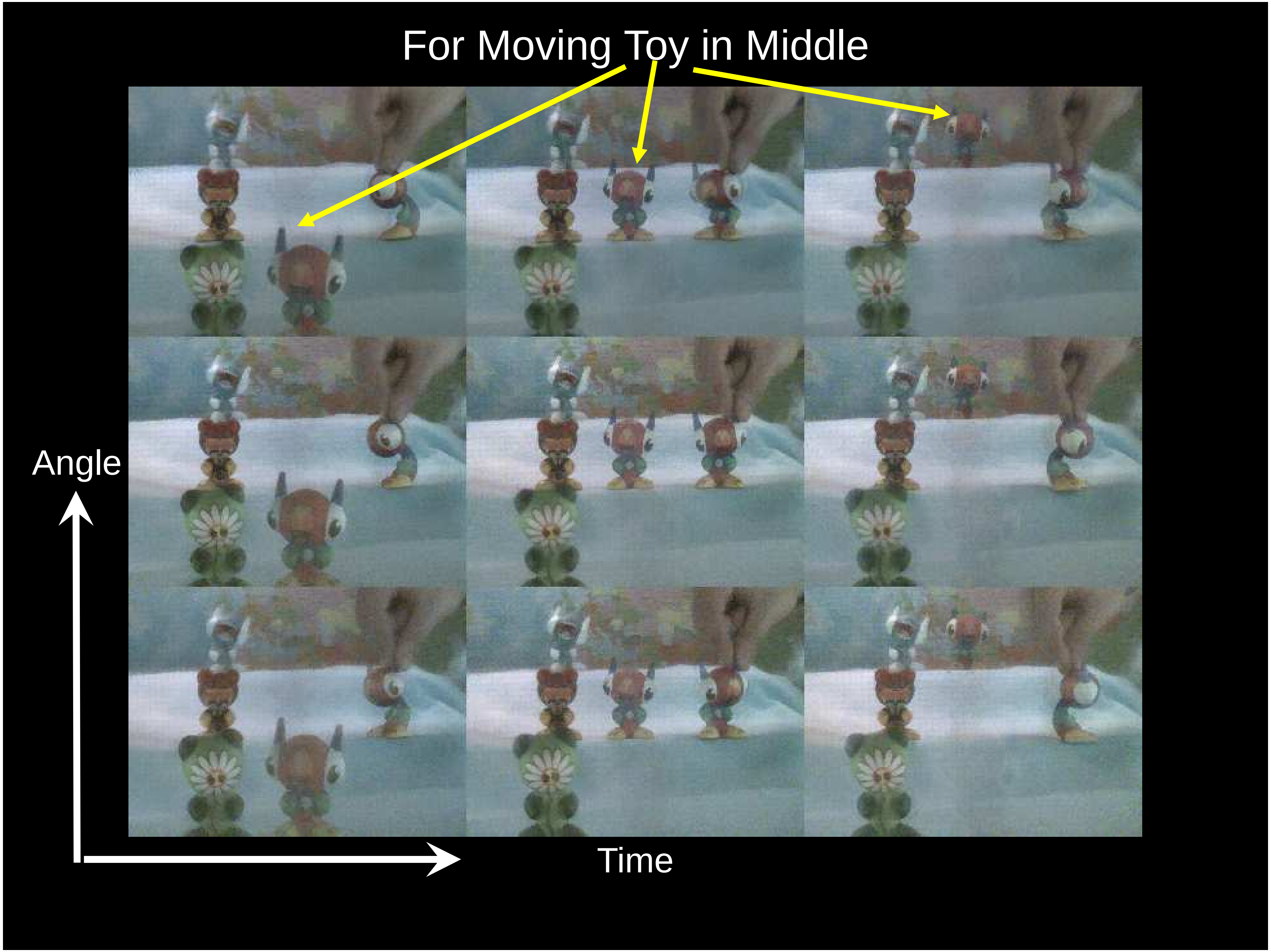


All Static and Dynamic Objects are sharp

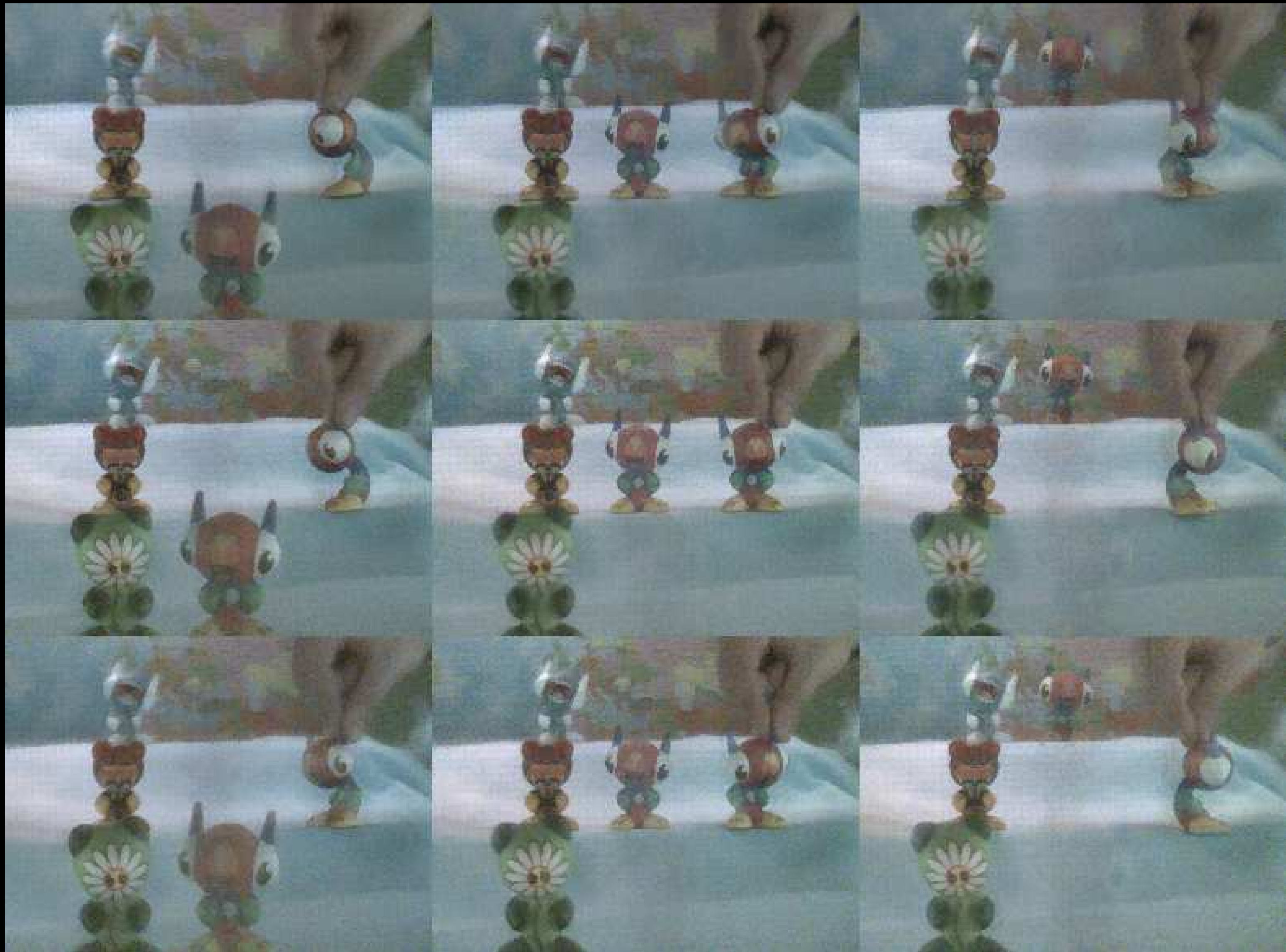
(No focus blur, no motion blur)

For Static Objects



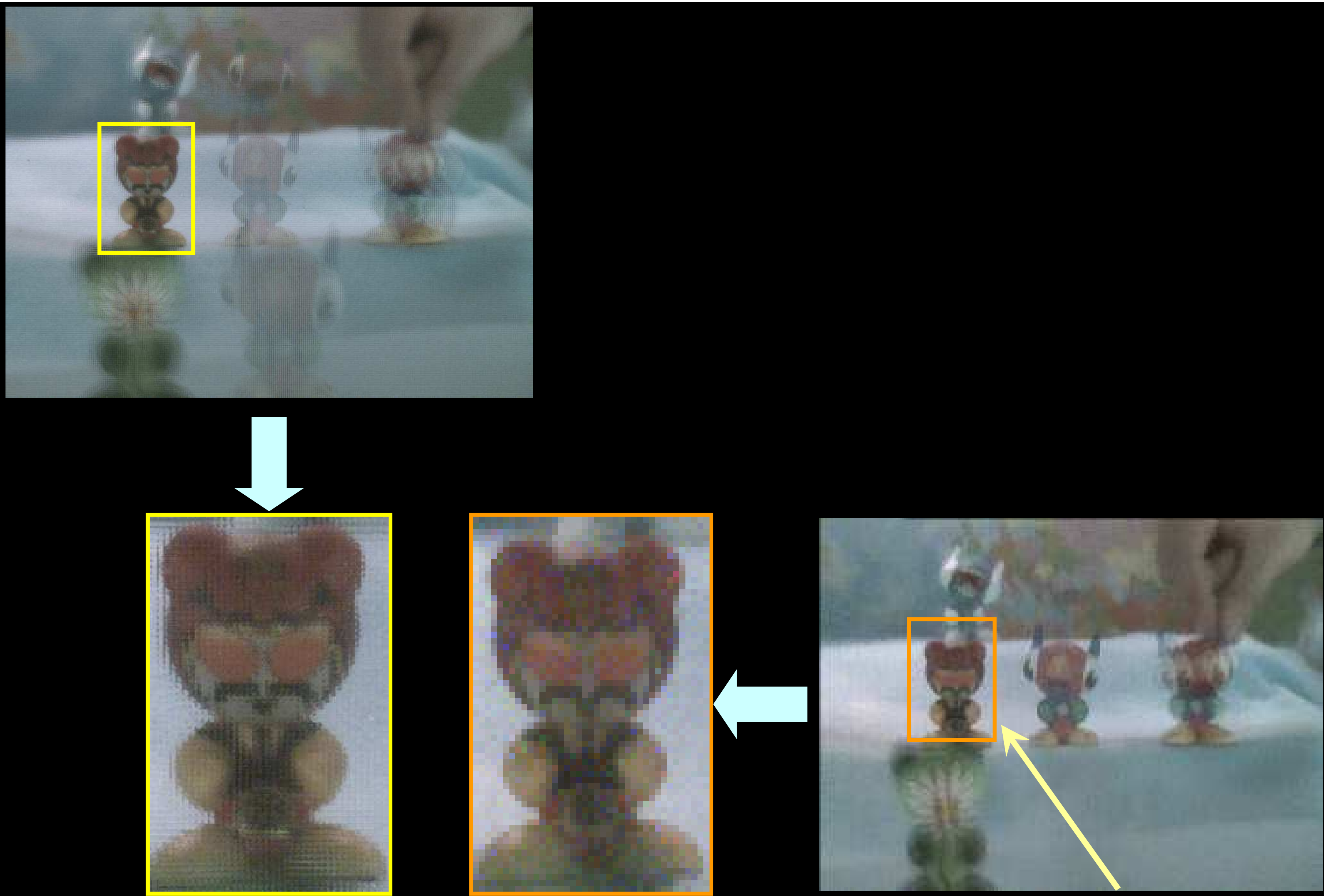

For Moving Toy in Middle
Angle
Time

For Rotating Toy on Right



Time

Time



High Resolution Image

Refocused on Static Toy

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Toy Moving in Depth

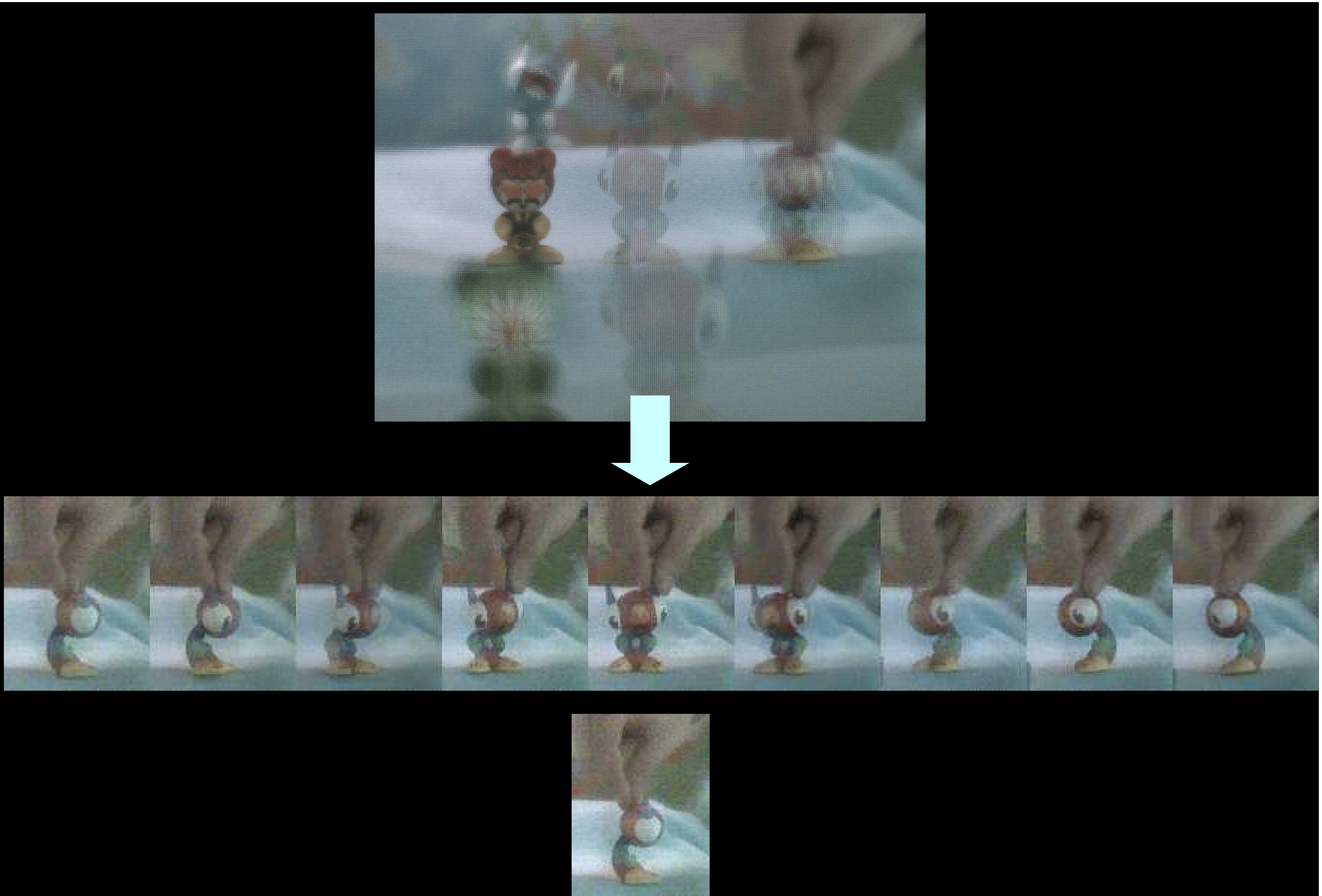
Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth



Video for Rotating Toy in-focus

Computational Cameras

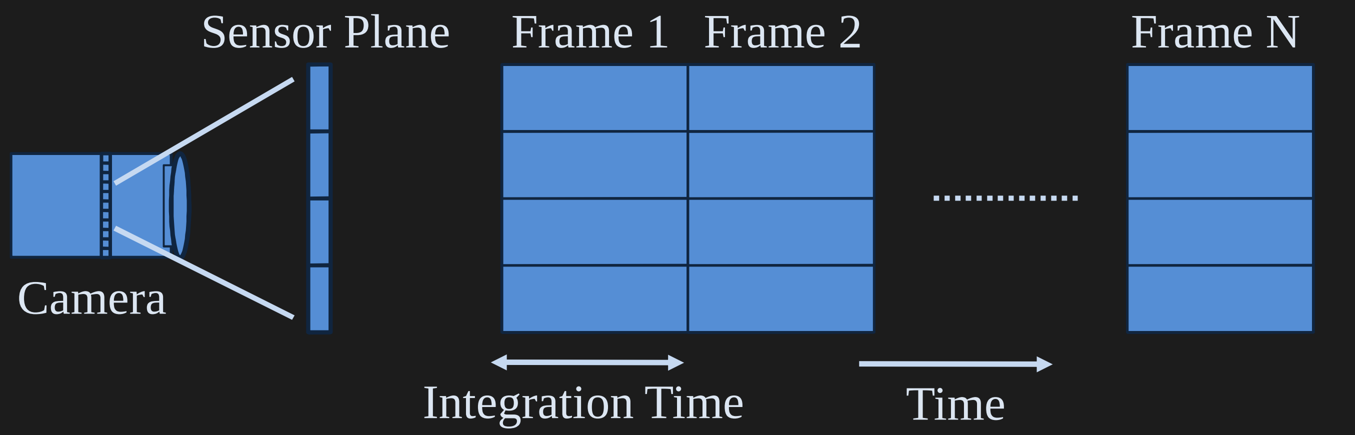
Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time, Angle
Flexible Voxels	Space and Time

Flexible Voxels

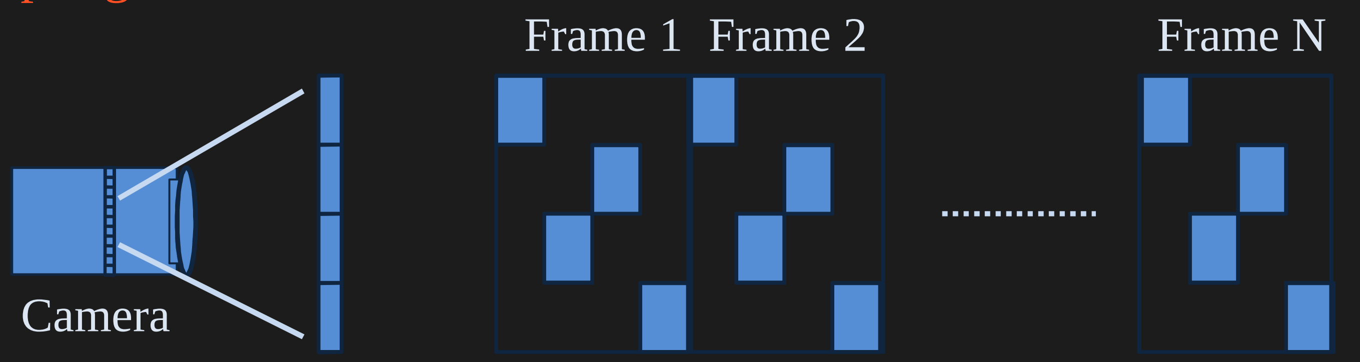
- Similar idea as Reintepretable Camera
  - But for videos
- Traditional Video Camera
  - Spatial/Temporal Resolution is fixed
  - Scene Independent
- Flexible Voxels
  - ‘Motion Aware’ Video Camera
  - Scene dependent variable resolution

Sampling of the Space-Time Volume

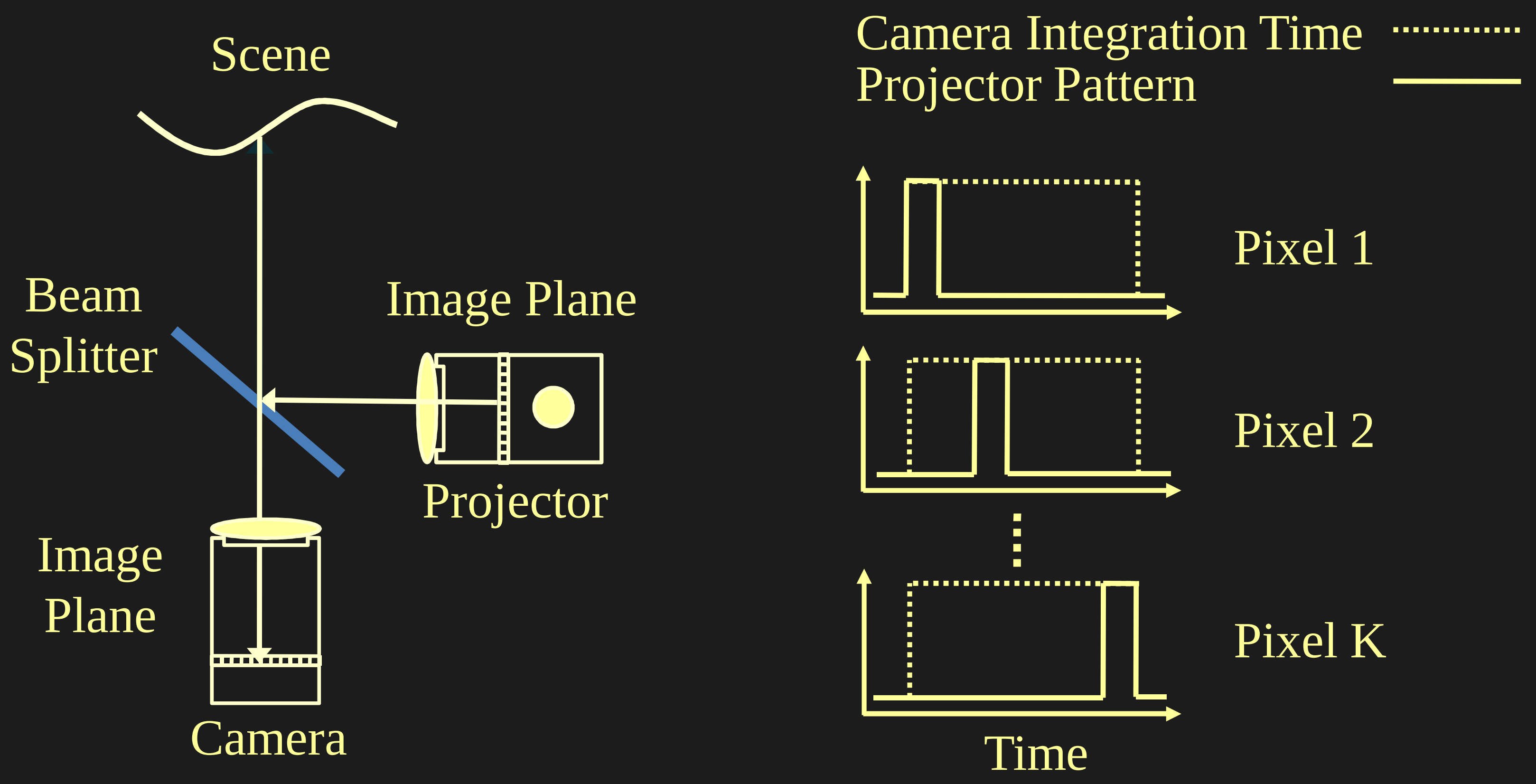
Conventional Sampling Scheme:



Our Sampling Scheme:

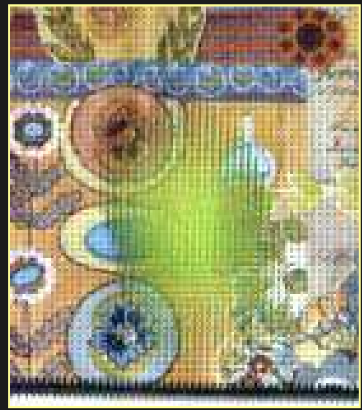


Co-located Projector-Camera Setup



Multiple Balls Bouncing and Colliding (15 FPS)

Large Motion Blur



Close-up

Motion-aware Video

Increasing Temporal Resolution

Captured Frame

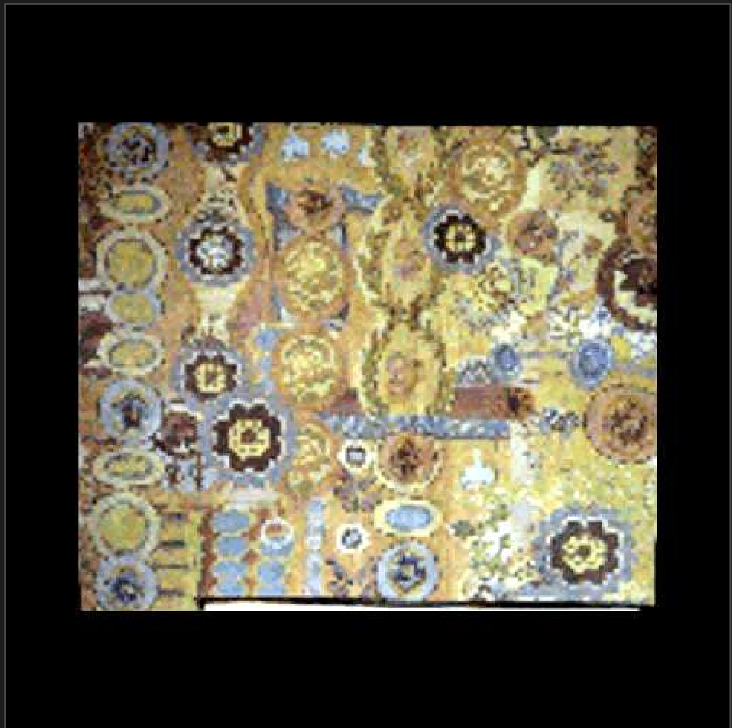
Different Spatio-temporal Interpretations

Motion
Analysis

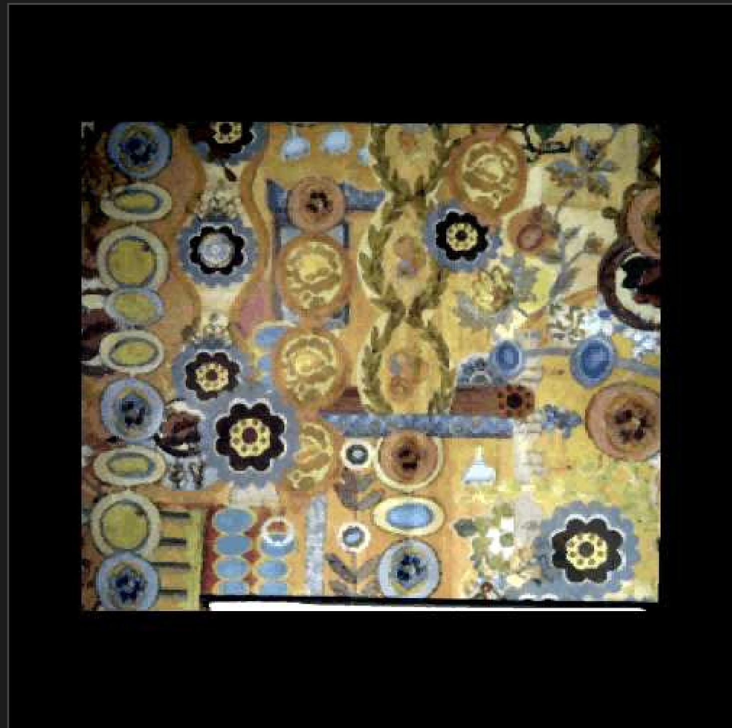
Motion-Aware Video

Optical Flow Magnitudes

Motion-aware Video

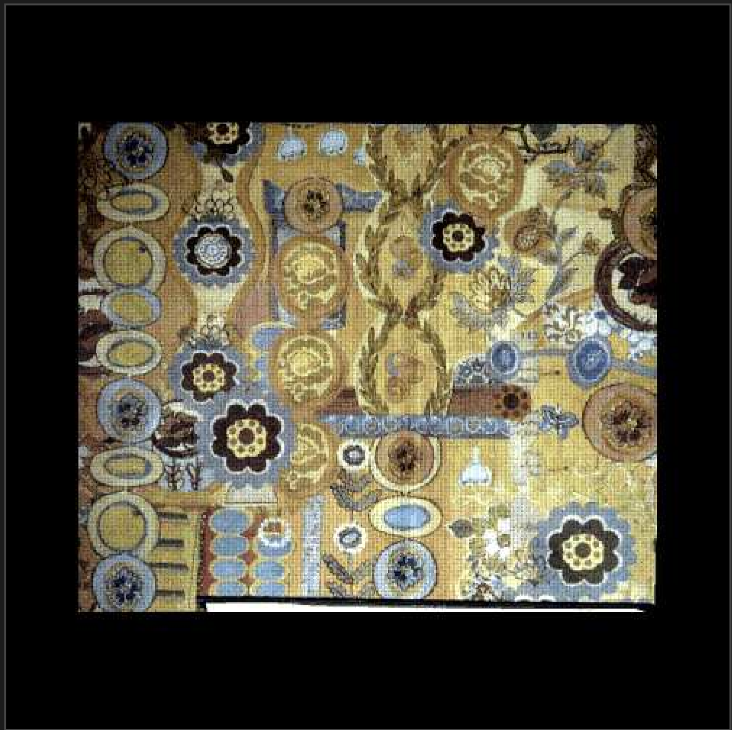


Simple Rebinning

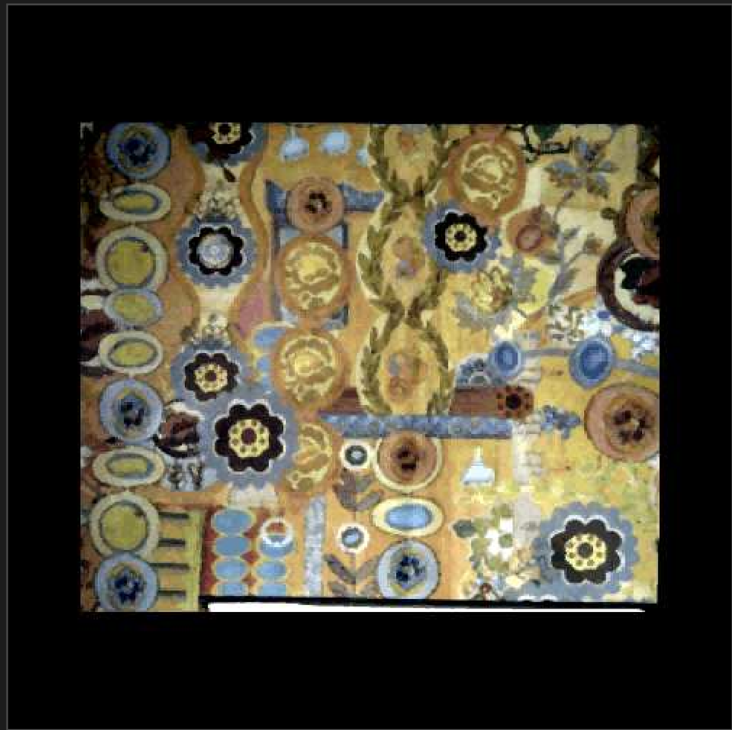


Motion-Aware Video

Multiple Balls Bouncing



Input Sequence



Motion-Aware Video

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time and Angle
Flexible Voxels	Space and Time

Common Implementation using fast programmable LCD's

- Light Field Mode
- Reinterpretable Mode

Computational Cameras and Illumination

- Cameras
  - Per-Pixel Control
  - Modulation in other dimensions: wavelength
  - Slicing and Sampling of Plentoptic function
- Reconstruction algorithms
  - Image/video based priors, compressive sensing
  - Statistical properties of plenoptic function
- Projectors
  - Angular (Directional) Control
  - 4D (light field) Projectors

Acknowledgements

- Ramesh Raskar, MIT
- Ashok Veeraraghavan, Rice Univ.
- Mohit Gupta, Columbia Univ
- Jack Tumblin, Northerwestern Univ
- Ankit Mohan
- Srinivasa Narasimhan, CMU
- Cyrus Wilson

- MERL, Jay Thornton, Joseph Katz, John Barnwell
- MELCO, Japan

Computational Cameras and Illumination

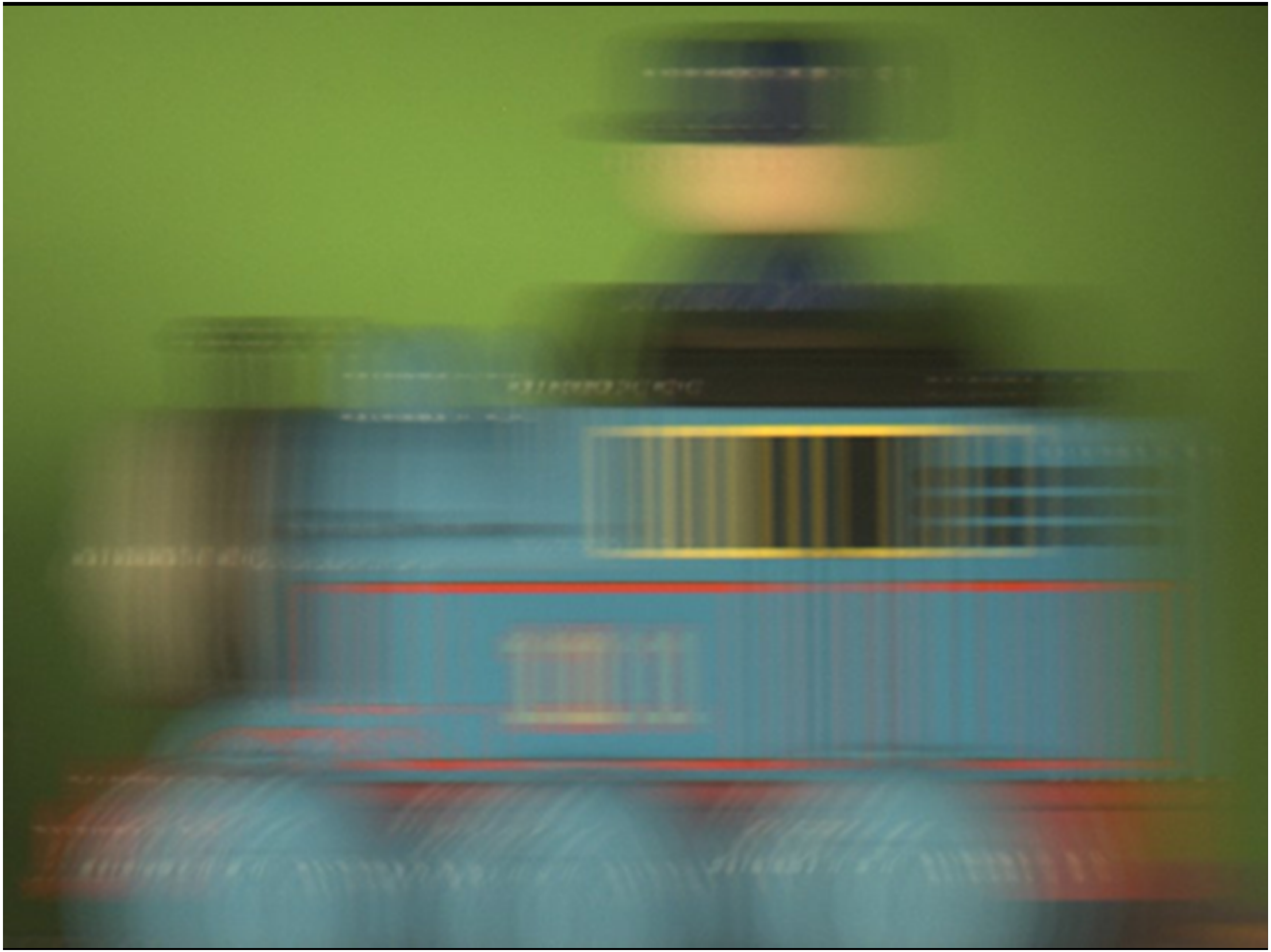
- Computational Illumination (Projector)
  - Structure Light
  - Design of new codes
  - Global Illumination

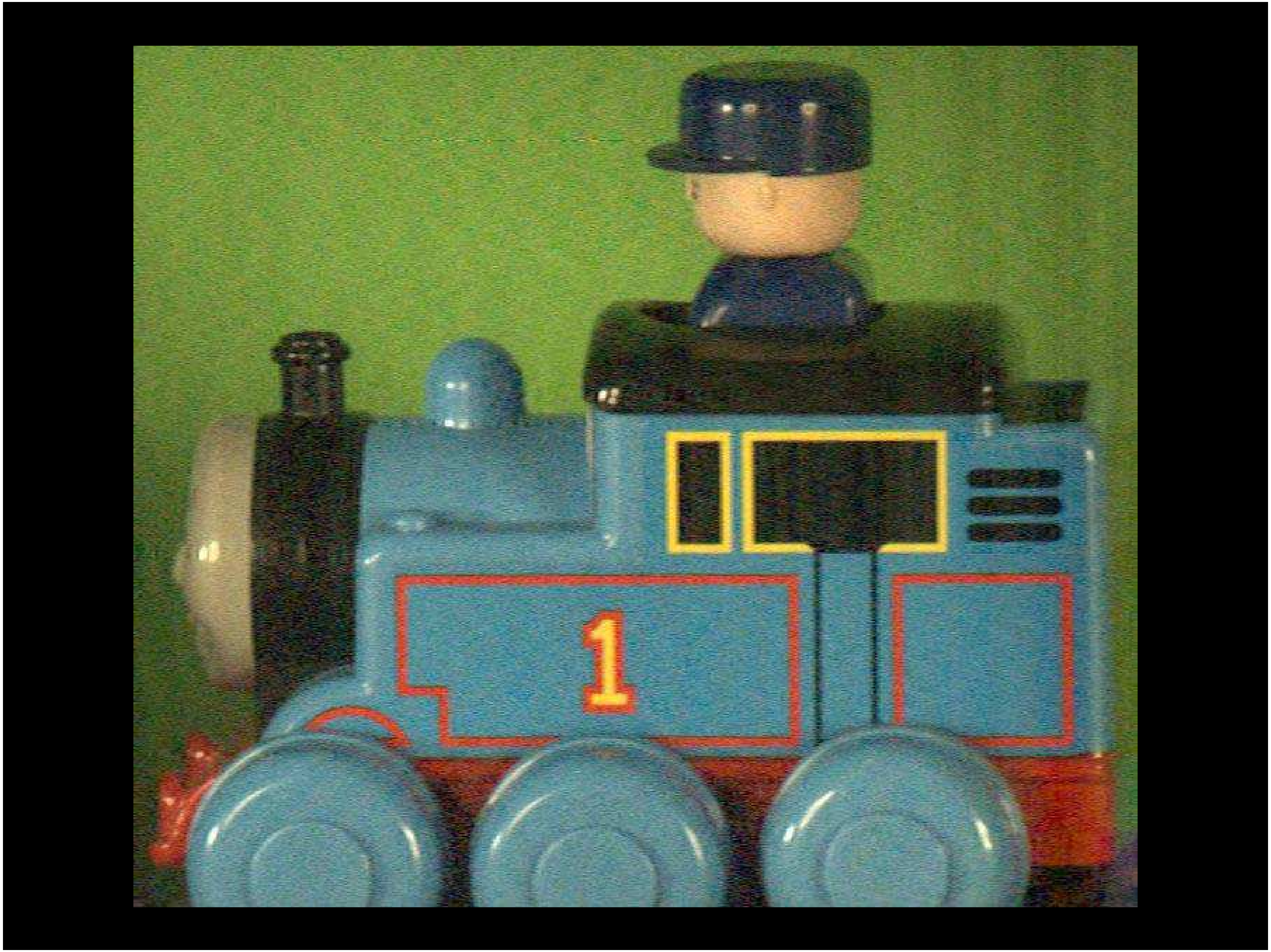
- Computational Cameras
  - Motion Blur, Focus Blur, Light Fields, Plenoptic Function

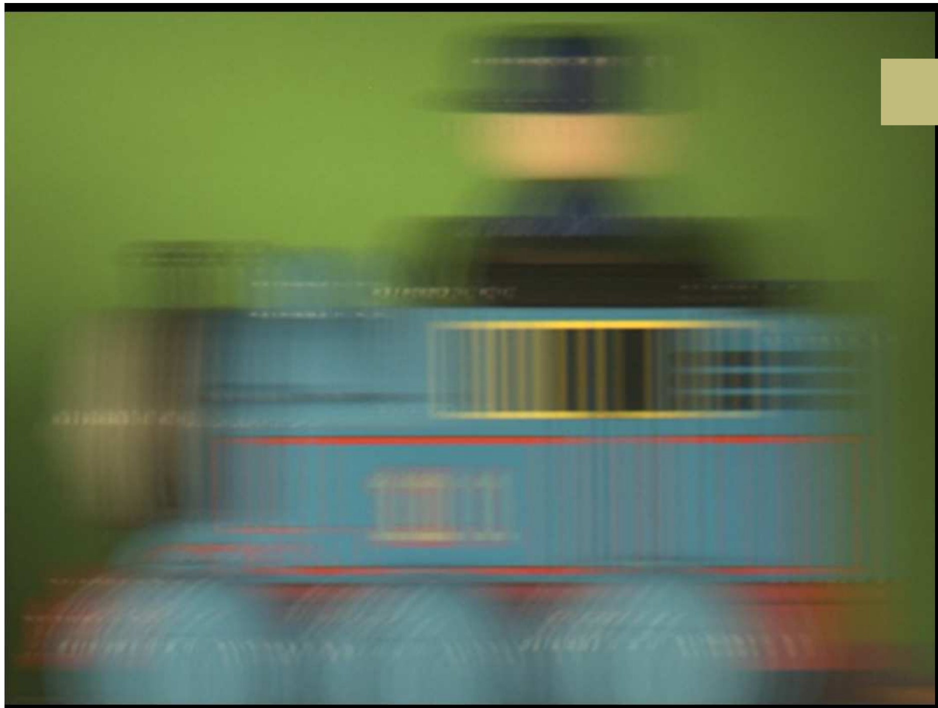

Input Image

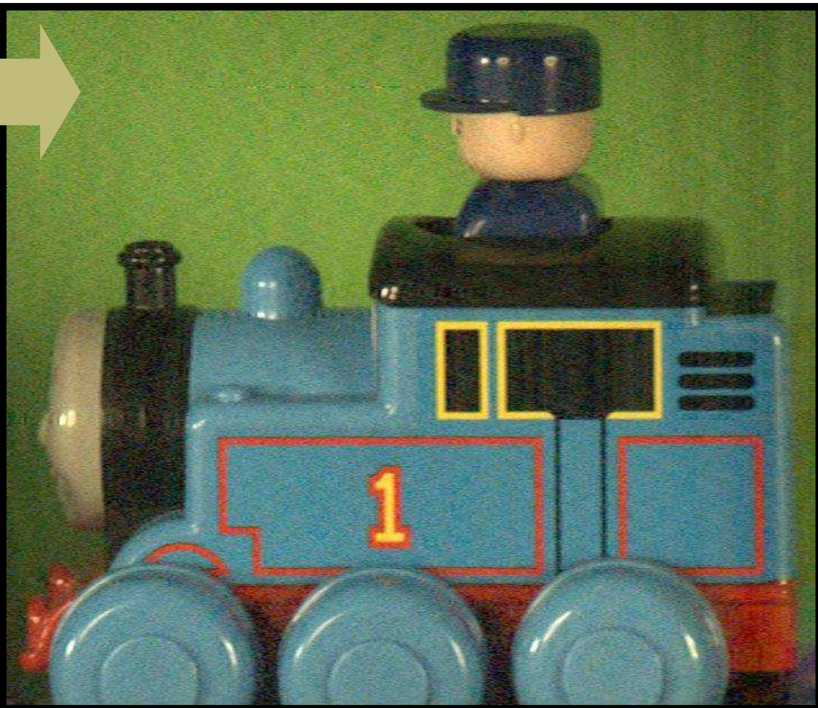
Rectified Crop

Deblurred Result



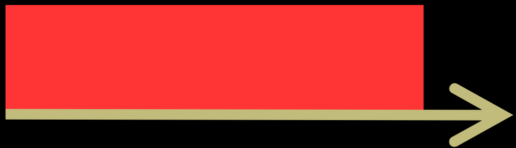

1





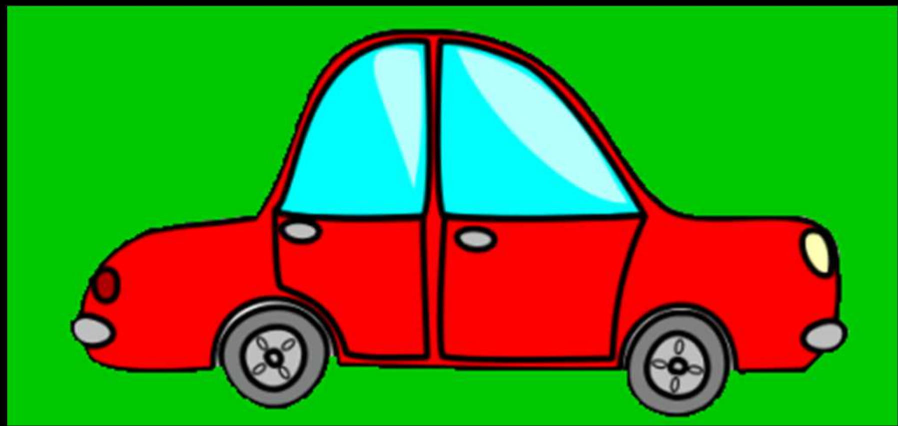
Input Photo

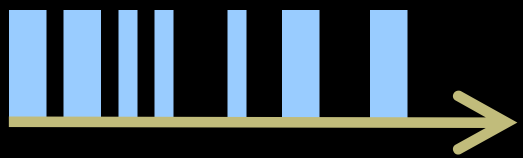
Deblurred Result



Traditional Camera

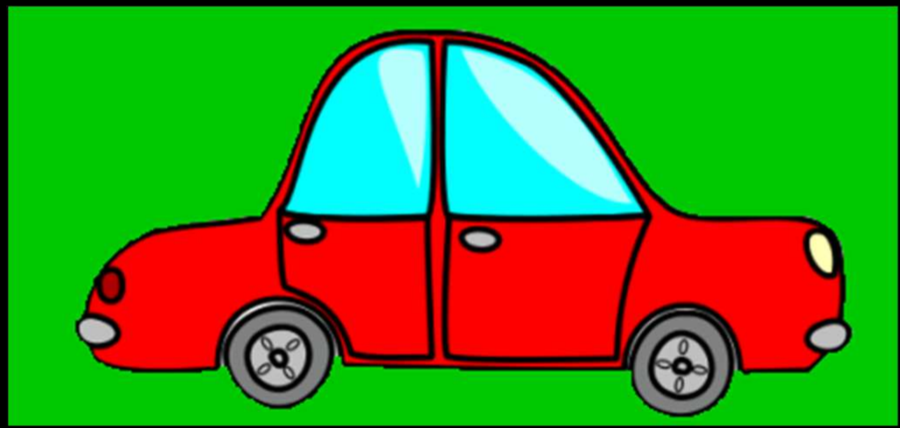
Shutter is OPEN

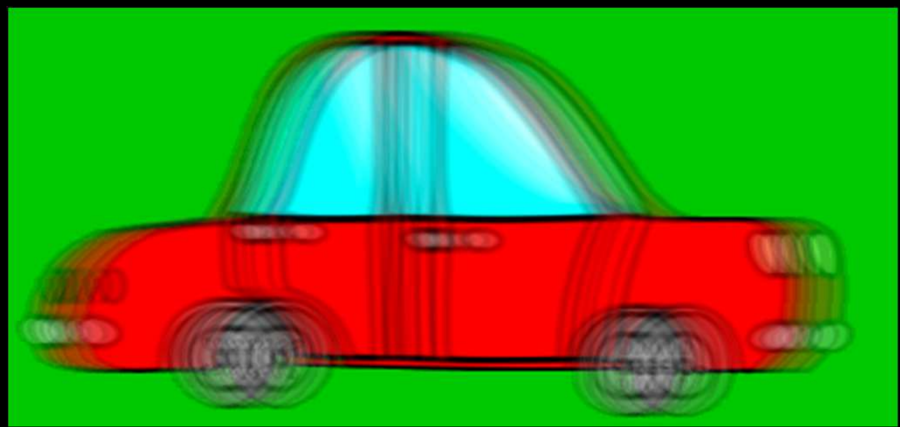




Our Camera

Flutter Shutter





Shutter is OPEN
and CLOSED